Energy-Efficient and Overhead-Aware Cooperative Communications

Bleron Klaiqi

Department of Electronic and Electrical Engineering
University of Sheffield

This dissertation is submitted for the degree of
Doctor of Philosophy

September 2017

I dedicate this thesis to my family.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

Bleron Klaiqi
September 2017

Acknowledgements

I was very fortunate to receive support from many great people. Without their sincere help this thesis would not have been possible.

First of all, I would like to thank my first supervisor Dr. Xiaoli Chu for her great support, guidance, and continues encouragement. Her deep knowledge, immense energy and dedication were a great source of inspiration. I deeply appreciate all her efforts to provide productive and stimulating research environment.

Furthermore, I would like to thank my second supervisor Dr. Wei Liu for his support and guidance. My sincere appreciation also goes to Prof. Jie Zhang for invaluable comments and fruitful discussions.

The financial support of EPSRC, EEE Department of the University of Sheffield, and Horizon 2020 project DECADE are also gratefully acknowledged.

I am also grateful to my parents for their love, understanding and continuous support in all the difficulties encountered during these years.

I thank my wife for her love, understanding, and support throughout these years. And a special thanks to my little son Mat who awaited me patiently during the writing of this thesis.

Abstract

Due to the rapid growth of energy-hungry wireless multimedia services, telecom energy consumption is increasing at an extraordinary rate. Besides negative environmental impacts and higher energy bills for operators, it also affects user experience as improvements in battery technologies have not kept up with increasing mobile energy demands. Therefore, how to increase the energy efficiency (EE) of wireless communications has gained a lot of attention recently.

Cooperative communication, where relays cooperatively retransmit the received data from the source to the destination, is seen as a promising technique to increases EE. Nevertheless, it requires more overhead than direct communication that needs to be taken into account for practical wireless cooperative networks. In order to achieve potential energy savings promised by cooperative communications in practical systems, overhead-aware cooperative relaying schemes with low overhead are imperative.

For the case that not all relays can hear each other, i.e., hidden relays exist, an energy-efficient and a low-overhead cooperative relaying scheme is proposed. This scheme selects a subset of relays before data transmission, through the proactive participation of available relays using their local timers. Theoretical analysis of average EE under maximum transmission power constraint, using practical data packet length, and taking account of the overhead for obtaining channel state information (CSI), relay selection, and cooperative beamforming, is performed and a closed-form approximate expression for the optimal position of relays is derived. Furthermore, the overhead of the proposed scheme and the impact of data packet lengths on EE, are analysed. The analytical and simulation results reveal that the proposed scheme is significantly more energy-efficient than direct transmission, best relay selection, all relay selection, and a state-of-the-art existing cooperative relaying scheme. Moreover, the proposed scheme reduces the overhead and achieves higher energy savings for larger data packets.

The conventional cooperative beamforming schemes rely on the feedback of CSIs of the best relays from the destination, which cause extra energy consumption and are prone to quantization errors in practical systems. In the case of clustered relays with location

awareness and timer-based relay selection, where relays can overhear the transmission and know the location of each other, an energy-efficient overhead-aware cooperative relaying scheme is proposed, making CSI feedback from the destination dispensable. In order to avoid possible collisions between relay transmissions during best relays selection, a distributed mechanism for the selected relays to appropriately insert guard intervals before their transmissions is proposed. Average EE of the proposed scheme considering the related overhead is analysed. Moreover, the impact of the number of available relays, the number of selected relays and the location of relay cluster on EE is studied. The simulation results indicate that the proposed cooperative relaying scheme achieves higher EE than direct communication, best relay selection, and all relay selection for relay clusters located close to the source. Independent of the relay cluster location, the proposed scheme exhibits significantly higher EE than an existing cooperative relaying scheme.

Device-to-device (D2D) communication in cellular networks that enable direct transmissions between user equipments (UEs) is seen as a promising way to improve both EE and spectral efficiency (SE). If the source UE (SUE) and the destination UE (DUE) are far away from each other or if the channel between them is too weak for direct transmission, then two-hop D2D communications, where relay UEs (RUEs) forward the SUE's data packets to the DUE, can be used. An energy- and spectral-efficient optimal adaptive forwarding strategy (OAFS) for two-hop D2D communications is proposed. In a distributed manner, the OAFS adaptively chooses between the best relay forwarding (BRF) and the cooperative relay beamforming (CRB) with the optimal number of selected RUEs, depending on which of them provides the higher instantaneous EE. In order to reduce the computational complexity of relay selection, a low-complexity sub-optimal adaptive forwarding strategy (SAFS) is proposed that selects between the BRF and the CRB with two RUEs by comparing their instantaneous EE. Theoretical analysis of the average EE and SE for the proposed adaptive forwarding strategies is performed considering maximum transmission power constraints, circuit power consumption and the overhead for the acquisition of CSI, forwarding mode selection and cooperative beamforming. The theoretical and simulation results show that the proposed OAFS and SAFS exhibit significantly higher EE and SE than the BRF, CRB, direct D2D communications and conventional cellular communications. For short to moderate SUE-to-DUE distances, SAFS is almost as energy- and spectral-efficient as OAFS.

Table of contents

List of figures

List of tables

Abbreviations

3GPP	3rd Generation Partnership Project
AF	Amplify-and-Forward
AWGN	Additive White Gaussian Noise
BRF	Best Relay Forwarding
BS	Base Station
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CF	Compress-and-Forward
CRB	Cooperative Relay Beamforming
CSI	Channel State Information
CSMA	Code Sense Multiple Access
D2D	Device-to-Device
DF	Decode-and-Forward
EE	Energy Efficiency
GPS	Global Positioning System
H-ARQ	Hybrid-Automatic Repeat Request
HD	Half-Duplex
KKT	Karush-Kuhn-Tucker

LTE-A	Long Term Evolution-Advanced
M2M	Machine-to-Machine
MAC	Medium Access Control
MGF	Moment Generating Function
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MRC	Maximum Ratio Combining
OAFS	Optimal Adaptive Forwarding Strategy
OFDM	Orthogonal Frequency Division Multiplexing
P2P	Peer-to-Peer
PDF	Probability Density Function
PER	Packet Error Rate
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RF	Radio Frequency
SAFS	Sub-Optimal Adaptive Forwarding Strategy
SE	Spectral Efficiency
SIMO	Single-Input Multiple-Output
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Ratio
STBC	Space Time Block Coding
STC	Space Time Coding
TDD	Time Division Duplex
UE	User Equipment

Chapter 1

Introduction

1.1 Motivation

Energy efficiency (EE) has become a crucial performance metric in wireless communications due to increasing energy consumption resulting from increasingly widely deployed wireless communication systems and devices [1]-[3].

Cooperative communication is seen as a promising technique to improve EE of wireless networks [4][5]. At least two nodes cooperate to form a virtual antenna array [6]. Each node in the wireless cooperative network, beside being a source node, that has its own data to transmit, it acts also as a relay for other nodes and forwards their data. Decode and forward (DF) and amplify and forward (AF) are the most common relaying protocols [7]. The DF relays first decode the received signal, then re-encode and retransmit it. In the case of AF relays the received signal from the source is amplified and then forwarded to the destination. Cooperative communications increase robustness to wireless channel impairments, as multiple copies of the source information are received at the destination. This phenomenon is known as spatial diversity and it can be exploited to reduce transmission power and hence improve EE. Moreover, cooperations split single-hop communications into two-hop communications that exploit nonlinear dependence of path loss on the distance to reduce transmission power.

Device-to-Device (D2D) communication, where user equipments (UEs) transmit directly to each other using cellular resources and without going through the base station (BS), is considered as one of the key techniques in Long Term Evolution-Advanced (LTE-A) [8]. D2D communications show great potential to improve EE and spectral efficiency (SE) [9]. In real world scenarios, the channels conditions between UEs may be not so favourable for the direct transmission. In this case, other UEs could act as relays and aid the communications between D2D UEs in a two-hop fashion [10][11].

Relay selection is one of the main challenges in designing energy-efficient cooperative communications. Various approaches have been used in the literature that can be divided into two main groups: best relay selection [12]-[14] and multiple relay selection [15]-[17]. In the first group only the best relay, according to a certain performance metric, is selected to retransmit the source information to the destination. Multiple relay selection methods recruit all available relays to assist communication between source and destination. Cooperative beamforming [17] and distributed space time coding (STC) [18] are the main coordination techniques for multiple relays transmissions. In the case that full channel state information (CSI) is available at the relays, cooperative beamforming is the optimal precoder and achieves fully diversity [19].

One important aspect of cooperative communications that is widely ignored in the literature is the related overhead required to implement cooperative relaying in practical systems. It encompasses the overhead to obtain CSI, to select best relays and to coordinate the transmissions from selected relays. Obviously, the overhead need for cooperative relaying is higher than that for direct communications between source and destination and it leads also to additional energy consumption. Incorporating overhead in energy consumption analysis of cooperative communications leads to a trade-off between involving more relays to reduce energy consumption through cooperative gains and reduction of overhead via recruiting less relays [20]. This underpins the importance of including overhead in energy consumption analysis of cooperative communications.

Few works exist that study EE of cooperative communications and take into account the related overhead [17][20][21]. Works done so far either ignored the maximum transmission power constraint or assume very long data packets. The length of data packets is restricted by the channel coherence time. The assumption of very long data packets simplifies the analysis of EE but may disguise the actual effect of overhead on EE of cooperative communications. Furthermore, the impact of cooperative relay locations on EE has not been investigated yet.

In order to reveal the true potential of cooperative communications to improve EE and SE of practical wireless cooperative networks, besides considering practical systems and realistic conditions it is essential to devise overhead-aware cooperative communication schemes that reduce the required overhead and enable efficient implementation of cooperation.

1.2 Main Contributions

The main contributions of this thesis are:

- For the case that relays cannot overhear each other's transmissions, a new energy-efficient and low signalling overhead cooperative relaying scheme is proposed that proactively selects a subset of available relays before data transmission, using timers set at relays. Its performance in terms of EE and required signalling overhead is compared to a state-of-the-art cooperative relaying scheme, best relay selection, all relay selection, and direct transmission.

- Theoretical analysis of average EE considering practical constraints such as maximum transmission power and practical data packet length is performed. Furthermore, signalling overhead analysis factoring in the costs for channel estimation, relay selection and cooperative beamforming, is carried out.

- The impacts of the number of correctly decoding relays, relay location, and data packet length on the optimal number of relays that maximizes EE is studied. The number and location of cooperating relays are identified that maximize EE for given number of correctly decoding relays, source-to-destination distance, and data packet length.

- The expression of average EE for the proposed cooperative relaying scheme and a closed-form approximate expression of the optimal location of cooperating relays as a function of the numbers of correctly decoding relays and selected relays are derived. The accuracy of the expressions is evaluated through simulations.

- For location-aware clustered cooperative beamforming, where relays know the locations and can overhear transmissions of each other, an energy-efficient cooperative communication scheme is proposed that combines overhearing capabilities of relays, location awareness and low-overhead timer based relay selection to enable each selected relay to calculate the second-hop channel power gains of other selected relays, which are required for them to perform optimal cooperative beamforming. In this way, CSI feedback from the destination is not needed.

- In order to avoid possible collisions between relay transmissions, a distributed mechanism for the selected relays to insert appropriate guarding intervals before their transmissions is proposed.

- For a two-hop D2D communications overlaying cellular networks, a novel energy- and spectral-efficient optimal adaptive forwarding strategy (OAFS) is proposed that in a distributed manner and dynamically switches between the best relay forwarding (BRF) and the cooperative relay beamforming (CRB) with an optimal number of RUEs, depending on which of them exhibits the higher instantaneous EE. The proposed adaptive forwarding strategy consists of two main steps. In the first step, all correctly decoding RUEs form a main cluster, and the RUE with the strongest second-hop channel in the main-cluster is selected using timers set at RUEs. In the second step, the remaining RUEs with their first-hop channels no weaker than that of any selected RUE, if any, form a sub-cluster; the RUE with the strongest second-hop channel in the sub-cluster is selected to perform cooperative beamforming with the selected RUE(s) if it improves the instantaneous energy efficiency; otherwise, BRF is performed. The second step repeats until the best RUE selected from the sub-cluster cannot improve the instantaneous EE any more or all RUEs from sub-cluster are selected for cooperative beamforming.

- In order to reduce the computational complexity, a distributed low-complexity sub-optimal adaptive forwarding strategy (SAFS) is proposed, where at most two RUEs, i.e., the best RUE in the main-cluster and the best RUE in the sub-cluster, are selected using timers set at RUEs to perform CRB if CRB shows a higher instantaneous EE than BRF; otherwise, BRF is performed.

- Theoretical analysis of average EE and SE for two-hop D2D communications utilizing the proposed optimal and sub-optimal adaptive forwarding strategies is performed. The performance of the proposed forwarding strategies is compared to BRF, CRB with the optimal number of RUEs, direct D2D communications, and conventional cellular communications.

1.3 Thesis Outline

The rest of the thesis is organized as follows.

In Chapter 2, the relevant literature on cooperative communications is reviewed. Furthermore, some of the concepts used later in the thesis, are explained in more details.

For the general case that relays may not be able to overhear each other's transmissions, in Chapter 3 an energy-efficient and overhead-aware cooperative relaying scheme with low overhead is proposed. Moreover, theoretical analysis for average EE and overhead of the proposed scheme is carried out. Closed-form expression for optimal relay location is derived. Average EE of the proposed scheme is compared to existing relaying schemes and direct transmission.

In Chapter 4, EE of clustered cooperative communications with location-awareness is studied, where relays are organized in clusters and can overhear the transmissions and know the location of each other. A cooperative beamforming scheme is proposed that exploits overhearing capabilities and location-awareness of relays as well as timer-based relay selection to avoid CSI feedback from the destination. Furthermore, a distributed mechanism for the selected relays to appropriately insert guard intervals before their transmissions is proposed to avoid possible collisions between relay transmissions. The optimal number and location of cooperating relays that maximize EE of the proposed scheme are identified. State-of-the art existing schemes and direct transmission are used as a benchmark for the proposed cooperative communication scheme.

In Chapter 5, EE and SE of overhead-aware two-hop D2D communications under maximum transmit power constraint and considering constant circuit power consumption is investigated. A new energy and spectral efficient optimal adaptive forwarding strategy is proposed that dynamically and in distributed way chooses between best relay UE forwarding and cooperative RUEs beamforming with an optimal number of RUEs, depending on which of them shows higher instantaneous EE. Moreover, a sub-optimal forwarding strategy with low complexity is proposed that adaptively and depending on instantaneous EE switches between best relay UE forwarding and cooperative RUEs beamforming with two RUEs. Average EE and SE of the proposed forwarding strategies is analysed theoretically and their performances are compared to best relay UE forwarding, cooperative RUEs beamforming with an optimal number of RUEs, direct D2D communications, and cellular communications.

Finally, the conclusions and some possible future research directions are provided in Chapter 6.

1.4 List of Publications

Chapter 3:

1. B. Klaiqi, X. Chu and J. Zhang, "Energy-efficient cooperative beamforming using timer based relay subset selection," *IEEE Wireless Communications and Networking Conference (WCNC)*, New Orleans, LA, USA, 2015.
2. B. Klaiqi, X. Chu and J. Zhang, "Energy-Efficient and Low Signaling Overhead Cooperative Relaying With Proactive Relay Subset Selection," *IEEE Transactions on Communications*, vol. 64, no. 3, pp. 1001-1015, March 2016.

Chapter 4:

3. B. Klaiqi, X. Chu and J. Zhang, "Energy efficiency of location-aware clustered cooperative beamforming without destination feedback," *IEEE International Conference on Communications (ICC)*, London, UK, 2015.

Chapter 5:

4. B. Klaiqi, X. Chu and J. Zhang, "Energy and Overhead Aware Adaptive Forwarding Strategy for Multi-Hop Device-to-Device Communications," *IEEE CAMAD*, Lund, Sweden, 2017.
5. B. Klaiqi, X. Chu and J. Zhang, "Energy-Efficient Multi-Hop Device-to-Device Communications with Adaptive Forwarding Strategy," *IEEE Global Communications Conference (GLOBECOM)*, Singapore, 2017.
6. B. Klaiqi, X. Chu and J. Zhang, "Energy and Spectral Efficient Adaptive Forwarding Strategy for Multi-Hop Device-to-Device Communications Overlaying Cellular Networks," *submitted to IEEE Transactions on Wireless Communications*, 2017.

Chapter 2

Background and Related Work

The concept of cooperative communication has been introduced for the first time in the pioneering work [22], where upper and lower capacity bounds of general relay channel have been derived. It considered a three node system composed of a source, a relay and a destination as depicted in Fig. 2.1. The communication via relay channel consists of

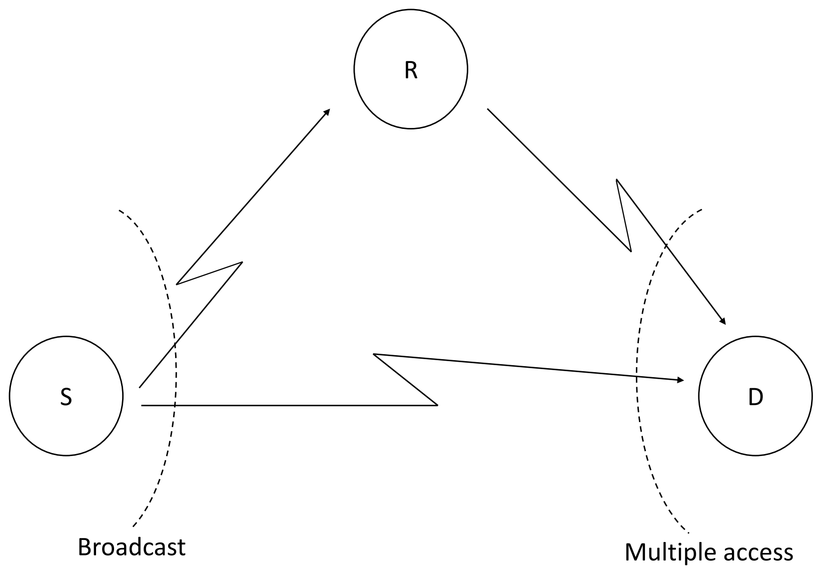


Fig. 2.1 Relay channel

two modes: broadcast and multiple access. In the broadcast mode, source transmits while relay and destination receive. In the multiple access mode, relay and source transmit, while destination receives. The capacity for a Gaussian relay channel is evaluated in [23].

Inspired by the potential of spatial diversity to improve system performance in a fading channel, two mobile user's cooperation in Code Division Multiple Acces (CDMA) system as depicted in Fig. 2.2 is proposed in [6]. Orthogonal spreading codes are assigned to cooperating users. It has been shown that beside expanding rate region for two users, user cooperation reduces outage probability and increases cell coverage in a cellular system. Nevertheless, user cooperation increases complexity at mobile users receiver as they have to be able to decode uplink signals. Practical issues for mobile users cooperation are investigated in [24].

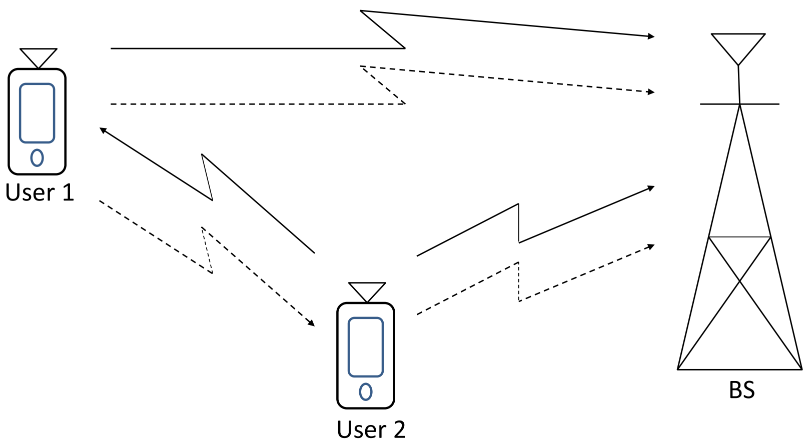


Fig. 2.2 Two user cooperation

It is demonstrated that even under different practical limitations cooperation outperforms no-cooperation case.

2.1 Main Relaying Protocols for Cooperative Communications

The main relaying protocols are: decode-and-forward (DF), amplify-and-forward (AF), and compress-and-forward (CF) Relaying.

2.1.1 Decode-and-Forward (DF) Relaying

Also known as regenerative relaying, for this protocol relay decodes and re-encodes the received signal from the source prior to forwarding it to the destination. The DF relaying is realized via two transmission phases.

In the first phase, source transmits a signal to relay. The received signal at relay is given by

$$y_r = \sqrt{P_1} f_r s_1 + n_r, \tag{2.1}$$

where y_r, s_1, f_r, and $n_r \sim \mathcal{N}\left(0, \sigma_1^2\right)$ are received signal at relay, source transmitted signal with power P_1 and $\mathbb{E}\{|s_1|^2\} = 1$, channel gain between source and relay, and additive white Gaussian noise (AWGN) at relay, respectively.

Relay first decodes then re-encodes the received signal and then in the second phase forwards it to the destination. The received signal from DF relay at destination is given by

$$y_d = \sqrt{P_2} f_d \tilde{s}_1 + n_d, \tag{2.2}$$

where y_d, $\tilde{s}_1$, f_d, and $n_d \sim \mathcal{N}\left(0, \sigma_2^2\right)$ denote received signal at destination, relay transmitted signal with power P_2, and $\mathbb{E}\{|\tilde{s}_1|^2\} = 1$, channel gain between relay and destination, and AWGN at destination, respectively.

The capacity of DF relaying link is determined by the weakest channel among the transmission phases and is given by [7]

$$C_{DF} = \frac{1}{2} \min \left[\log\left(1 + |f_r|^2 \frac{P_1}{\sigma_1^2}\right), \log\left(1 + |f_d|^2 \frac{P_2}{\sigma_2^2}\right) \right]. \tag{2.3}$$

The factor of $1/2$ is due to the half-duplex (HD) relaying.

In [7], diverse low complexity cooperation protocols have been developed using fixed, selection and incremental relaying. Fixed relaying can be easy implemented but has low bandwidth efficiency. It achieves a diversity order one. In selection relaying, only if the received SNR exceeds a certain threshold, relays decode and forward received message. Diversity order two is obtained. Finally, for incremental relaying, one feedback channel from the destination to the relay is assumed to indicated success or failure of the direct transmission. The relay retransmits only when destination could not decode the source message. This protocol exhibits the best spectral efficiency (SE) and achieves diversity order two.

2.1.2 Amplify-and-Forward (AF) Relaying

For this non-regenerative relaying, relay first amplifies the received signal from the source and then forwards it to the destination.

Analogous to DF relaying protocol, the transmission is performed in two phases. The received signal y_r at AF relay during the first phase is obtained by (2.1). In the second phase, relay forwards the amplified version of y_r, i.e., $Gy_r = \sqrt{\frac{P_2}{|f_r|^2 P_1 + \sigma_1^2}} y_r$ with transmission power P_2, where G is gain factor. The signal received at destination is obtained as follows

$$y_d = f_d G y_r + n_d = f_d \sqrt{\frac{P_2}{|f_r|^2 P_1 + \sigma_1^2}} \left(\sqrt{P_1} f_r s_1 + n_r\right) + n_d, \tag{2.4}$$

The capacity of AF relaying link is given by [7]

$$C_{AF} = \frac{1}{2} \log \left(1 + \frac{|f_d|^2 |f_r|^2 P_2 P_1}{P_2 |f_d|^2 \sigma_1^2 + P_1 |f_r|^2 \sigma_2^2 + \sigma_1^2 \sigma_2^2}\right). \tag{2.5}$$

2.1.3 Compress-and-Forward (CF) Relaying

In CF relaying, relays refrain from decoding the source signal, instead the received signal is compressed, re-encoded and then forwarded to the destination [23]. CF relays can use conventional source coding or Wyner–Ziv (WZ) coding [25] for compressing the received signal. WZ coding enables a CF relay to compress the source signal using the correlation between its received signal and the signal at the destination. Joint decoding and side information are utilized at the destination to recover the transmitted signal. CF relaying is preferable for relays located in the vicinity of the destination due to high correlation of the received signals at relay and destination. Various coding schemes for CF relays such as turbo codes [26], lattice codes [27] and polar codes [28] have been proposed in the literature.

2.2 Relay Selection Schemes in Cooperative Communications

In order to harvest performance gains of cooperative communication, relay selection plays a crucial role. Relay selection algorithms can be implemented in two main ways: centralized and distributed. In centralized relay selection, one node is chosen to act as a central controller that collects all necessary information and selects then one or multiple relays to assist communication between source and destination. Although, in this case global optimum can be achieved, significant amount of overhead is required, especially for large number of relays. Distributed algorithms provides usually suboptimal solution for relay selection problem, nevertheless, compared to centralized algorithms, overhead and complexity are reduced [12][29]-[32]. Besides the implementation of relay selection algorithm, also the number of relays selected to retransmit the data to destination, has significant effect on the performance of cooperative communication systems. Two main groups can be distinguished: single relay selection schemes using one node to assist the communication and multiple relay selection schemes, where more than one relay retransmit the data to the destination [33].

2.2.1 Single Relay Selection Schemes

Performance of cooperative networks using best DF relay and direct link is analysed in [34]. The relay with highest signal-to-noise ratio (SNR) to the destination is selected as the best relay. It is shown that full diversity order is achieved. A forwarding scheme that selects the relay with the shortest distance to the destination is proposed in [32]. It is assumed that each relay knows its own and destination location. This distributed single relay selection scheme reduces the system complexity, however it cannot achieve optimal performance as the effect of shadowing and multipath fading is not considered.

An opportunistic relay selection scheme that selects best relay in distributed manner based on the instantaneous CSI has been presented in [35]. Two relay selection policies have been analysed. Policy I selects the relay that maximizes the minimum of link strengths in first and second hop. Policy II chooses the relay that maximizes the harmonic mean of two hops. In order to select the best relay in distributed way with minimal overhead, each relay starts a timer that is inversely proportional to relaying link quality according to one of the policies mentioned above. The timer of relay with the best relaying quality for the proposed policies will expire first. There is a probability that timers of two or more relay expires within the same time interval leading to collision and failure of relay selection. As it is shown collision probability can be made arbitrarily small at the cost of increased relays selection time. Thus, collision probability has to be traded off for speed of relay selection. Through simulation and theoretical analysis, it has been demonstrated that policy I exhibits lower outage probability than policy II. Moreover, impact of four different relay topologies (close to the source, in the middle, close to the destination and relays are located equidistantly in a line network) on collision probability has been investigated. The relays close to the source lead to the lowest collision probability. The proposed opportunistic relaying shows the same diversity-multiplexing tradeoff as space-time coding. Due to simplicity and distributed nature, timer-based relay selection is very appealing. Nevertheless, it may fail to select best relay due to exceeding of maximum selection time or collision of two or more packets when the timers of two or more relays expire within vulnerability window. In [36], a general timer scheme with monotone non-increasing metric to timer function has been studied. Optimal staircase metric-to-timer mapping is proposed that maps the metrics in discrete timer values and depends on maximum relay selection time and vulnerability window. This scheme maximizes the probability of successful relay selection or minimizes the expected relay selection time. It has been shown that the proposed scheme clearly outperforms the inverse metric mapping [35] in terms of both probability of relay selection and expected relay selection time. In [37], optimal timer mapping has been generalized in two ways by assuming first that only the distribution of nodes is a priori known to all nodes and second that neither number of nodes nor distribution of them is known, referred to as robust mapping. For both cases, it is shown that optimal timer mapping has still staircase structure. Moreover, robust mapping not only exhibits highest worst case success probability but is also robust to uncertainty in number of nodes.

Another class of distributed relay selection schemes are the geographical based relay selection schemes [12][38][32]. The relays are grouped in different geographical regions according to their distance to the destination [12]. Relays that belong to the region closest to the destination compete for the channel through carrier sense multiple access (CSMA) splitting scheme. In the case that no relays are found, the procedure continues with the second closest region and so on. It is assumed that relays are equipped with global positioning system (GPS) and know both their own location and the location of destination. The latency of the geographical based relay selection was studied in [38]. In [32], the correctly decoding relay that is closest to the destination is selected to serve hybrid-automatic repeat request (H-ARQ).

Opportunistic relay selection can be performed in proactive way prior to data transmission or in reactive manner after data transmission [39]. As depicted in Fig. 2.3, in proactive relay selection, the best relay is selected in the first phase before source transmits its data. Thus, during data transmission only the best relay is active while other relays enter idle mode. In the second phase, the selected relay forwards the received data to the destination. For the reactive relay selection, source transmits data that are received from all available relays. Subsequently, the best relay is selected for forwarding data to the destination.

Perfect synchronisation between the nodes and CSI of both hops are required for opportunistic relay selection schemes. Partial relay selection that needs only first-hop CSI and selects the relay with the strongest source to relay channel is investigated in [40]-[42]. In [40], a novel partial relay selection scheme is proposed that selects the best relay with the strongest first-hop channel out of subset of relays for which neither source to relay nor relay to destination channels are in outage. It outperforms conventional partial relay

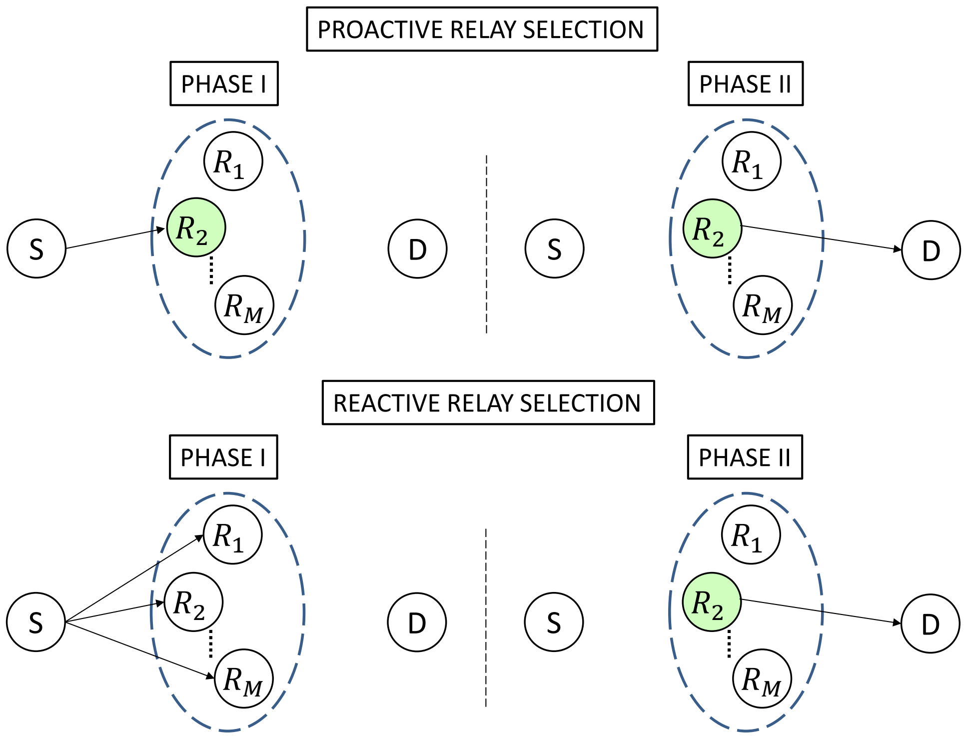


Fig. 2.3 Proactive and reactive relay selection

selection methods and exhibits comparable performance to the full CSI scheme. End-to-end performance for partial relay selection utilizing fixed gain AF relays that reduce system complexity, is studied in [41]. In [42], statistical behaviour of partial relay selection using variable gain AF relays is analysed.

The relaying schemes above suffer from loses in SE due to the HD transmission. Improvement of SE while maintaining the same diversity order is the main goal of the incremental relaying [43]-[45]. The main idea is that when the direct link is sufficiently strong there is no need to involve a relay in cooperative transmission. An incremental AF relaying scheme using best relay selection and adaptive modulation is proposed in [43]. It achieves significant gains in SE for low average SNR, while for high average SNR outage probability is considerably reduced. In order to decide whether to cooperate or not, the ratio between direct link channel gain and the best relaying link is compared to cooperation threshold [44]. In the case that this ratio is at least as big as cooperation threshold the source sends data directly to the destination without relay assistance, otherwise the source and the selected relay cooperative transmit data to the destination. It has been revealed that using this scheme, the bandwidth efficiency is significantly increased and full diversity is achieved. For incremental

DF opportunistic relaying very accurate closed form expression for outage probability is derived in [45].

2.2.2 Multiple Relays Selection Schemes

The idea of single relay selection has been generalized to multiple relay selection in [33]. Low complexity suboptimal multiple AF relay selection schemes have been proposed that exhibit full diversity and performance close to the optimal scheme. Performance analysis for different multiple relay selection scheme based on the orthogonal relaying has been performed in [46]-[48]. Various distributed optimal power allocation strategies for multiple DF relays transmitting in orthogonal slots are proposed in [49]. Adaptive multi-node incremental AF relaying is investigated in [50]. Destination carries out maximum ratio combining first on N earliest slots and based on output SNR decides whether to terminate transmission for remaining relays. The SE is improved compared to conventional schemes. In order to tackle HD loss, coded cooperation protocol for multiple DF relays network has been proposed in [51]. For this protocol each relay forwards only a chunk of codeword and destination composes the whole codeword from chunks received from all relays. The loss due to HD transmission becomes negligible with increasing number of relays.

The works mentioned above use orthogonal relaying, where relays retransmit at different time slots and hence do not make the best use of available channel resources. Two main cooperation strategies are utilized to leverage simultaneous multiple relays transmission: cooperative beamforming and cooperative space time coding.

Cooperative Beamforming

In cooperative beamforming as depicted in Fig. 2.4, at least two nodes transmit at the same time the received message and align their phases to enable coherent combining at destination. Deployment of cooperative beamforming is motivated by the gains achieved using multiple antennas at the transmitter known also as centralized beamforming. For transmit beamforming using L antennas, received power equals L^2-fold of single antenna transmission. This significant gain in received power can be exploited to improve energy efficiency (EE), increase data rate, extend coverage, reduce interference etc. Different from centralized beamforming, cooperative beamforming imposes additional practical challenges like timing, carrier and phase synchronisation among cooperating nodes. In [52], based on master-slave architecture a protocol is presented to tackle the problem of carrier phase synchronisation for distributed nodes. It is shown that beamforming gain is robust to modest phase errors resulting mainly from oscillators drifts. In the two nodes case for around 30° phase error 90% of ideal beamforming gain is achievable.

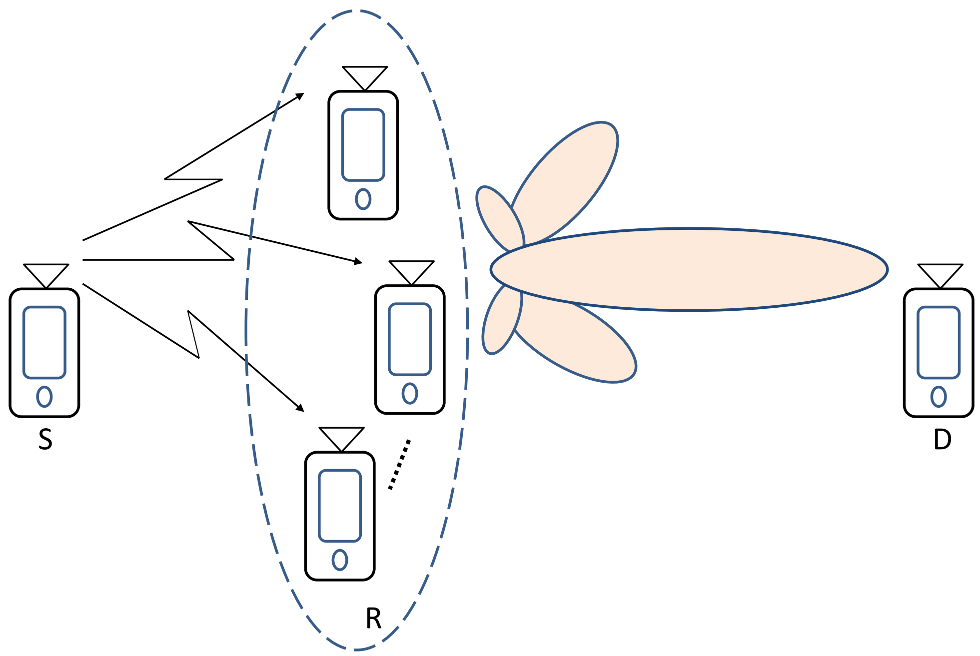


Fig. 2.4 Cooperative beamforming

Cooperative beamforming has been widely studied [19][52]-[55]. For cooperative networks optimum relay precoders and destination decoders have been developed in [19]. In the case that full CSI is available both at the relays and at the destination, it is proven that cooperative beamforming and maximum ratio combining (MRC) are optimal precoder and decoder, respectively. Further it is also shown that for this case full diversity order is achieved. Cooperative beamforming with limited feedback for AF relays has been investigated in [53]. It considered relay selection as a special case of beamforming, where the weight vectors are the columns of identity matrix. Outage probability of relay selection is compared to cooperative beamforming using optimal and random codebook. Beamforming using optimal codebook showed slightly lower outage probability, however at the cost of very high complexity. For the same number of feedback bits, relay selection outperformed cooperative beamforming with random codebook. Due to the reduced complexity offered by the proposed selection scheme (e.g. no synchronisation between relays required), it is very attractive for cooperative beamforming with limited feedback. Network beamforming for two step AF relays with perfect CSI availability and power constraint at each relay, has been analysed in [54]. It is shown that power control at relay for direct link available at first step is the same as for no direct link case. For the case that direct link is available only at second step or at both steps, recursive numerical power control algorithms are proposed. Simulation results show that the proposed network beamforming achieves full diversity and outperforms other conventional schemes. Cooperative beamforming for DF relays and limited feedback is studied in [55]. It is demonstrated that compared to single relay and all relay selection, using only a subset of relays lead to significant performance improvements in terms of average received SNR efficiency and outage probability.

Cooperative Space Time Coding

A space time coded cooperative protocol that provides full spatial diversity equal to the number of cooperating relays, has been proposed in [56]. This protocol improves bandwidth efficiency and requires no feedback from the destination. Two transmission phases are distinguishable. In the first phase source broadcast the message that is received by the destination and available relays. During the second phase, the relays that could successfully decode the message, cooperatively forward it to the destination using a unique column of space time code matrix and same sub-channel.

Best modulations and optimal transmission strategies for centralized and distributed Alamouti coded Multiple-Input Multiple-Output (MIMO), that minimize overall energy consumption, have been investigated in [15]. Besides transmission energy also circuit power consumption has been taken into account. It is shown that for short range communication and fixed modulation, Single-Input Single-Output (SISO) outperforms MIMO in terms of EE, as circuit power dominates energy consumption. Nevertheless, using MIMO with optimal constellation size can be more energy-efficient than SISO even for very short distances. This work also investigated the impact of node cooperation on the EE and the overall delay. Different cooperation possibilities have been considered: at transmitter Multiple-Input Single-Output (MISO), at receiver Single-Input Multiple-Output(SIMO) and at both side MIMO. Performance comparison between cooperative and non cooperative communications has been performed and showed that cooperation at the transmitter and/or receiver can reduce both energy consumption and transmission delay.

Energy and delay efficiency for cooperative MIMO considering also training energy consumption has been studied in [57]. Delay efficiency is defined as the delay reduction achieved by MIMO compared to SISO. It has been shown that even when the cost of training overhead is taken into account, cooperative MIMO outperforms SISO in terms of energy and delay efficiency. In [58], distributed space time coding scheme without decoding at relays has been proposed. Distributed linear dispersion (LD) code is applied among the relays, i.e., transmit signal at each relay is linear combination of received signals. For very high SNR same diversity and coding gain is achieved as for MIMO.

2.3 Energy Efficiency and Overhead of Cooperative Communications

Wireless cooperative communications is widely recognized as a promising technique to improve the EE of wireless networks [1][4][5][59][60]. EE analysis for cooperative transmission in wireless sensor networks is performed in [16][61]-[64]. In [61], the EE of single-hop, multi-hop and cooperative transmission have been compared under target packet loss rate and end-to-end throughput. It is shown that cooperation exhibits higher EE than single-hop and multi-hop transmission even for short distances when a feedback channel is available. For randomly distributed sensor nodes a sleeping strategy is proposed that significantly reduces energy consumption compared to direct transmission [63].

In [16], a wireless sensor network is analysed that consists of multiple sensor clusters. Each cluster has one cluster head that controls data routing. Cluster members have to listen only to their cluster head and using space time block coding (STBC) cooperatively transmit data received from the head only when they can correctly decode them. Data received from cluster are at first processed by cluster head and then broadcast to other members. In this way virtual MISO for inter cluster communication is formed. Through simulations, the impact of cluster size, intra and inter cluster distances, power allocation, and end to end packet error rate (PER), is studied. Both transmit and receive circuit energy consumption is considered. It is demonstrated that optimal number of sensor in the cluster exists and it varies for different PER. Furthermore, significant energy savings compared to direct communications can be obtained.

Numerous works investigated energy savings through cooperation in wireless ad-hoc networks [17][21][65][66]. Furthermore, EE of cooperative relaying has been widely studied in the context of wireless cellular networks [14][67]-[70]. In [67], for uplink transmission in a cellular network consisting of two users, two relay nodes and a BS, an energy-efficient cooperative relaying scheme based on Alamouti STBC is proposed. The effectiveness of Alamouti coding in improving the EE of cooperative relaying has been also shown in [68]. Energy consumption for relay assisted uplink transmission is analysed in [70]. It is shown that relaying beside being beneficial for cell edge users is also useful for users closer to base station (BS).

The impact of relay selection on EE has been widely studied [13][71][72]. In [71], an energy-efficient opportunistic cooperative scheme is presented that switches between best DF relay forwarding and direct transmission depending on which one shows higher energy savings. For cooperative multiple relays MIMO network, energy efficient relay selection has been considered in [72]. EE of best relay selection scheme for wireless sensor networks has been investigated in [13]. The proposed scheme accounts for both medium access control (MAC) design and the power control at physical layer, i.e., it is a cross layer approach to design energy efficient selective cooperative wireless networks. Power control has been solved for two different relay selection cases. In the first case, the best relay that minimizes total energy consumption is selected, while in the second case the relay that maximizes the network lifetime is the one that retransmits data to the destination. It has been revealed by simulations, that the proposed scheme exhibits higher EE than direct communications and alternative schemes.

The overhead for obtaining CSI, relay selection and coordination is largely ignored in the literature. The impact of overhead on SE for three different relaying schemes: timer-based best-select (TBBS), distributed STC and M-group distributed STC, has been investigated in [18]. For the M-group distributed STC each of M correctly decoding relay selects randomly a column from STC matrix. Overhead is significantly reduced as there is no need for the destination to assign a unique column of STC matrix to each relay of the decoding set. The analysis revealed that distributed STC is impractical due to amount of overhead required for centralized implementation. TBBS achieves full diversity and hence is better for small SNR margin and small network size. M-group distributed STC exhibits the highest SE for large SNR margin and/or large network size.

The significance of the overhead in overall energy consumption has been demonstrated in [20]. It accounted for the cost to obtain CSI, perform cooperative beamforming and investigated more general relay selection method. Best relay and all relay selection emerge as special cases. Theoretical analysis for the overall energy consumption for both homogeneous and non-homogeneous channel is provided. For homogeneous channels, all links between the source and relays and from relays to the destination are statistically identical, while this is not the case for the non-homogeneous channels. Simulation results showed that using varying number of cooperative relays to perform cooperative beamforming minimizes energy consumption. The proposed relay selection rule provides energy savings of up to 16%. The inherent trade-off between relay selection overhead and data transmission in terms of time and energy is investigated in [73]. Cooperative non-adaptive and adaptive relay systems have been investigated. Optimal relay selection durations for different schemes are identified. Due to higher probability of successful transmission best relay selection lead to significantly higher throughput compared to random selection. Nevertheless, energy consumption during best relay selection phase is also high. For wireless ad-hoc networks, EE analysis accounting for overhead to form virtual beam towards the destination is investigated in [17]. It assumed that cooperating relays are uniformly distributed around the source and can overhear each other's transmissions. Simulation results indicated that cooperative beamforming is more energy and spectral efficient than direct communications. The number of relays that maximizes EE of cooperative beamforming has been calculated in [21]. Moreover, a switching algorithm that changes between direct and cooperative communications depending on which of them provides higher EE is also presented.

2.4 Two-Hop Device-to-Device Communications in Cellular Networks

Different from conventional cellular communication, where user equipments (UEs) communicate via BS, device-to-device (D2D) communications enable UEs to communicate directly to others UEs in its vicinity using cellular resources [9][74]-[76]. D2D communications show potential for three types of gains: proximity gain, reuse gain and hop gain [77]. D2D was first proposed for relaying user traffic [78]. Nowadays, new use cases have been introduced such as peer-to-peer (P2P) communications [79], cellular offloading [80], machine-to-machine (M2M) communications [81], and so on.

Direct communications between UEs can be realized using cellular spectrum (in-band [82][83]) or unlicensed spectrum (out-of-band [84][85]). For in-band communications, D2D links can share the same radio resources with cellular links (underlay [82]) or use dedicated cellular resources (overlay [83]) as depicted in Fig. 2.5. In underlay D2D, uplink [86] and downlink [87] spectrum resources can be deployed, leading to high SE. However, reusing spectral resources incurs mutual interference that is especially severe in the case that downlink spectrum resources are used for D2D [88]. Many works investigated the interference reduction for D2D underlaying cellular networks [89]-[92]. Based on the game theory, an effective spectrum resource allocation scheme for D2D underlay downlink cellular networks is proposed in [89]. New interference management method to increase the overall system capacity of D2D underlay uplink cellular networks is presented in [92]. For D2D

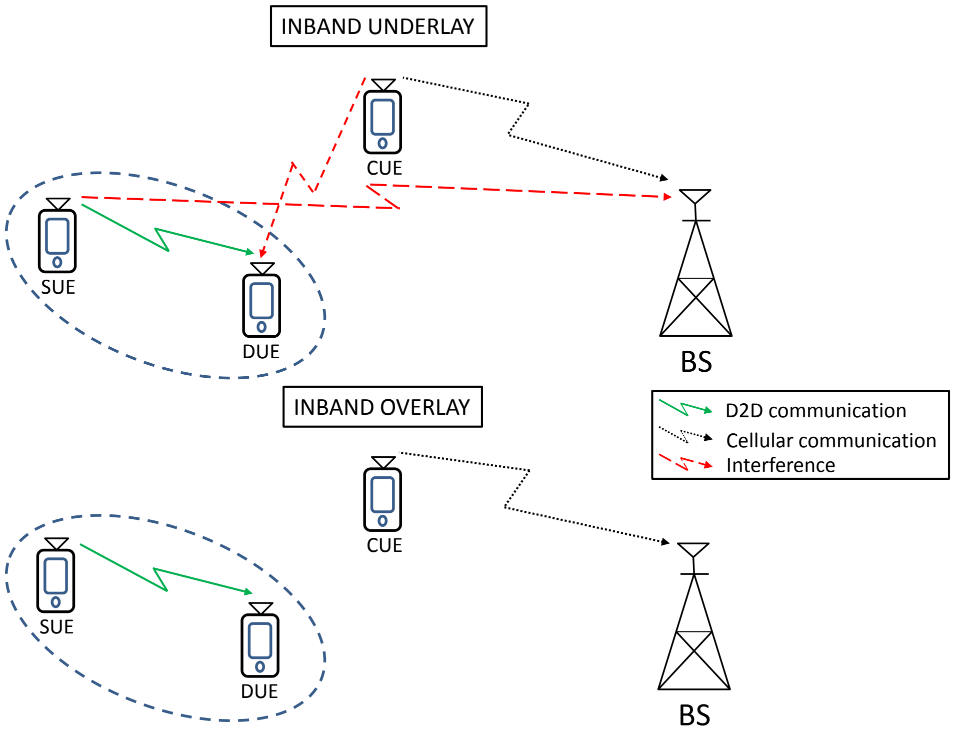


Fig. 2.5 In-band underlay and overlay D2D communication

overlaying cellular networks, interference limited areas are defined that forbid usage of same resources between D2D pairs and cellular users [83].

Besides interference management, mode selection between overlay, underlay and cellular communications is another critical issue in D2D communications [93]-[97]. In [93], a communication mode is selected according to the distance between involved devices. An optimal mode selection threshold is presented that minimizes the transmit power. Dynamic mode selection on a slot-by-slot basis that outperforms semi-static method, is proposed in [95]. For a D2D underlaying two-tier cellular networks, a centralized mode selection mechanism is considered in [97]. In the case that orthogonal resources are available, this mechanism prefers D2D overlay mode if D2D pairs are close to each other. Otherwise, underlay mode is selected if distance and interference criteria are fulfilled.

The works mentioned above mainly focus on improving SE of D2D communications, while EE is overlooked. Typical devices are handheld battery-powered equipment with limited capacity that make energy-efficient wireless communication imperative. Various energy-efficient D2D communication schemes have been proposed [98]-[102]. An energy-efficient and practical resource sharing D2D multimedia communications that rely on coalition formation game is presented in [98]. It addressed jointly mode selection and resource allocation. Furthermore, both transmission power consumption and circuit power consumption are taken into account. EE of mode switching under quality of service (QoS) guarantee for D2D pairs and cellular UEs is studied in [101]. The simulation results show that reuse mode is preferable if EE is the optimization objective, while dedicated mode is selected if user capacity has to be optimized. Moreover, dedicated mode will be selected more often with increasing radius of D2D pairs. For practical network scenarios, performance limit of energy savings for D2D communications underlaying cellular network is investigated in [102]. Simulation results indicated that D2D communications reduce the energy consumption by 65%. Trade-offs between energy consumption and delay, bandwidth, buffer size and throughput are attained that enable design of practical energy-efficient D2D communications.

In practice, D2D UEs might not be close to each other or channel conditions between them could be so poor that direct D2D communications would be impossible. Under these circumstances, relays could assist the communication between D2D UEs [10][11][103]-[107]. In [10], a distributed best relay selection method for relay aided D2D communication underlaying cellular network is proposed. This method coordinates the interference from/to cellular network and eliminates not suitable relays. Among the eligible relays the best one is selected. Relaying for sending emergency messages from disconnected areas in multi-hop fashion is considered in [103]. For L3 relay assisted D2D communications underlaying Long Term Evolution-Advanced (LTE-A) cellular networks, a gradient-based distributed resource allocation is proposed in [104]. This work is extended to consider also the uncertainties in useful and interference channels [106]. Furthermore, a distributed resource allocation algorithm is presented that relies on stable matching theory. Another distributed resource allocation scheme for L3 relay aided D2D communication that utilizes message passing approach on a factor graph is proposed in [105]. Joint relay selection, sub-channel and power allocation for relay aided D2D communications is investigated in [107]. An iterative Hungarian method is proposed as suboptimal solution with low complexity and near-optimal throughput performance. Energy and SE for multi-hop D2D communications based on a two-time-slot physical-layer network coding scheme and using orthogonal channel sharing is analysed in [11].

Chapter 3

Energy-Efficient and Low Signalling Overhead Cooperative Relaying with Proactive Relay Subset Selection

Energy efficiency (EE) of wireless communications has received a lot of attention recently owing to the tremendous energy demands resulting from widely deployed wireless networks and mobile personal devices. Cooperative communication is considered as a promising technique to enhance EE in wireless networks. Nevertheless, cooperation requires more overhead that makes overhead-aware cooperative schemes indispensable for practical implementation.

In this Chapter, an energy-efficient and overhead-aware cooperative relaying scheme is proposed and its average EE and signalling overhead is analysed. The number and location of relays is studied that maximize EE of the proposed cooperative communication scheme, taking into account the associated signalling overhead and practical constraints such as maximum transmission power, practical data packet lengths and the case that relays cannot overhear each other's transmissions.

The Chapter is organized as follows. The system model and the proposed cooperative relaying scheme are presented in Section 3.1. Section 3.2 presents the EE analysis. In Section 3.3, the optimal location of cooperating relays is derived. Signalling overhead analysis is performed in Section 3.4. The simulation results are presented in Section 3.5. Finally, summary is given in Section 3.6.

3.1 System Model and Cooperative Relaying Scheme

A wireless communication system is considered that consists of one source-destination pair and N decode-and-forward (DF) relays as shown in Fig. 3.1. Each node is equipped with a single omni-directional antenna. The channel power gains between the source and relay i $(i = 1, \ldots, N)$ and from relay i to the destination are given by h_i and g_i, respectively, which are independent and exponentially distributed random variables with the mean values, $\overline{h}_i = (\lambda_c/4\pi d_0)^2 (d_{si}/d_0)^{-\xi}$ and $\overline{g}_i = (\lambda_c/4\pi d_0)^2 (d_{id}/d_0)^{-\xi}$. Thereby, λ_c denotes the carrier wavelength, d_0 is the reference distance, ξ is the path-loss exponent, and d_{si} and d_{id} are the distances between source and relay i and between relay i and destination, respectively.

It is assumed that inter-relay distances are much smaller than those between the source and relays and from relays to the destination, i.e., we approximately have $\overline{h}_i = \overline{h}$ and $\overline{g}_i = \overline{g}$ $(i = 1, \ldots, N)$, where $\overline{h}$ and $\overline{g}$ denote the mean channel power gains of all links between source and relays and all links from relays to destination, respectively. Furthermore, channel reciprocity, i.e., time division duplex (TDD) mode is assumed, where the forward and reverse links between two nodes are identical and remain constant during the time period for training, relay selection, and data transmission [20][21].

It will be shown in Section 3.5 that the time required for training, relay selection and data transmission by the proposed scheme is much shorter than the channel coherence time of low mobility scenarios (with typical pedestrian speed of 3km/h). For higher mobility scenarios, data packets can be split into smaller packets and more signalling overhead is necessary as channel changes much faster. Communications between any two nodes have a rate R (bits/symbol) and bandwidth B (Hz). Perfect channel estimation and same noise power at each node are also assumed. No circuit power consumption is considered.

An energy-efficient and low signalling overhead cooperative relaying scheme is proposed, which can be divided into three main phases as illustrated in Fig. 3.1 and explained as follows.

3.1.1 Relay Channel Estimation Phase

Relays have to obtain first-hop CSI, in order to decode data from the source. To this end, source broadcasts training symbols at the minimum power required to support the target rate

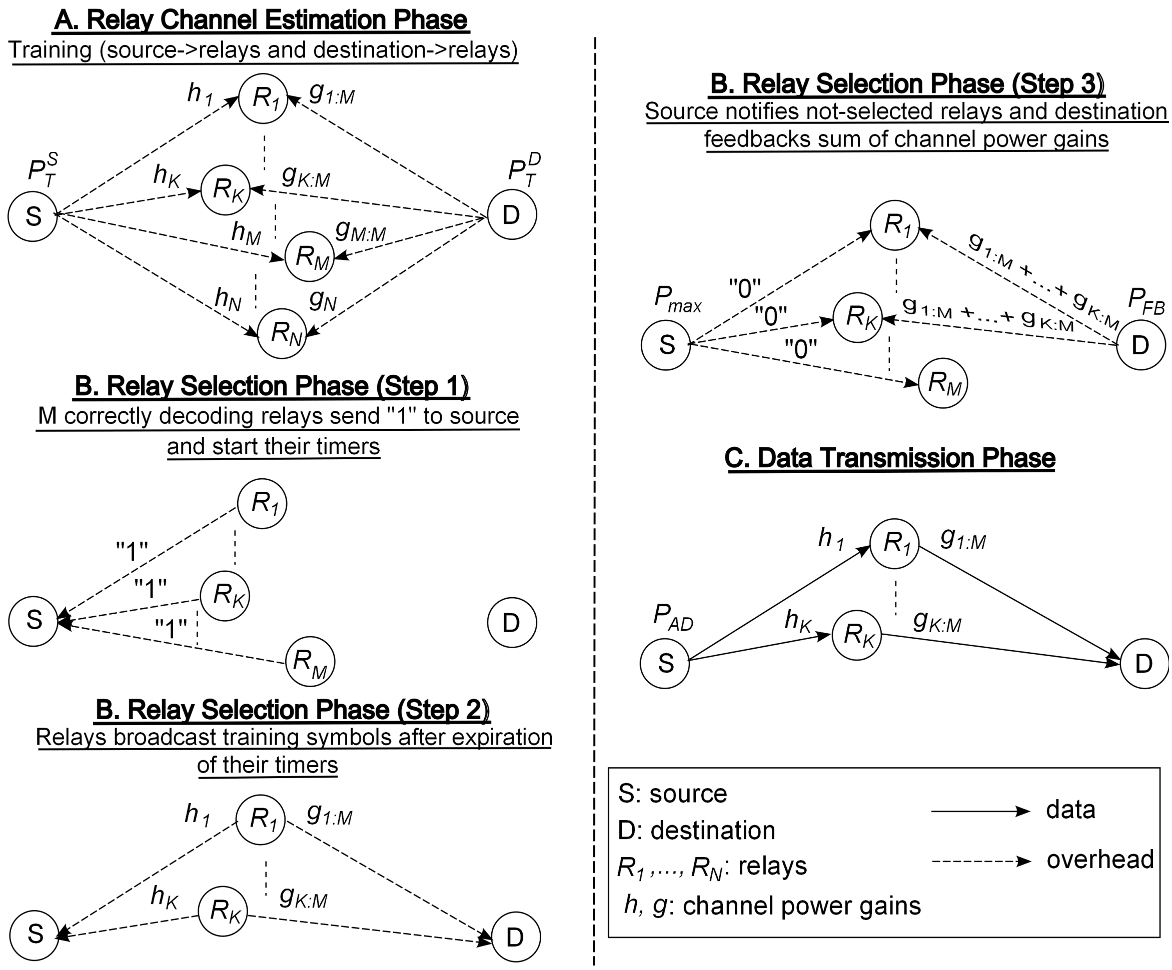


Fig. 3.1 Proposed cooperative relaying scheme

R with outage probability δ_{out}

$$\delta_{out} = Pr\left\{h_i \frac{P_T^S}{N_0 B} < 2^R - 1\right\} = \int_0^{\left(2^R-1\right)N_0 B/P_T^S} \frac{1}{\overline{h}} \exp\left(-\frac{x}{\overline{h}}\right) dx$$
$$= 1 - \exp\left(-\frac{\left(2^R - 1\right) N_0 B}{\overline{h} P_T^S}\right). \tag{3.1}$$

It follows then for the transmission power

$$P_T^S = N_0 B \frac{1 - 2^R}{\overline{h} \ln(1 - \delta_{out})}, \tag{3.2}$$

where N_0 is the power spectral density of additive white Gaussian noise (AWGN). Similarly, for relays to acquire the CSI on their links to the destination, the destination broadcasts training symbols with the following power,

$$P_T^D = N_0 B \frac{1 - 2^R}{\overline{g} \ln(1 - \delta_{out})}. \tag{3.3}$$

One way to ensure synchronisation between the source and the destination is to let the source broadcast training symbol in the first time slot within a channel coherence time. In the second time slot the destination broadcasts its training symbol.

3.1.2 Relay Selection Phase

Step 1: The set of correctly decoding relays, $\mathscr{D} = \{R_{1 \le j \le N} : \gamma_{sj} \ge 2^R - 1\}$, is composed of relays with the received signal-to-noise ratio (SNR) from the source, γ_{sj}, being able to support the rate R. Since the relays have estimated the channels from the source to them in the relay channel estimation phase, under the assumption of channel reciprocity the relays would also know the channels from themselves to the source. In Step 1 of the relay selection phase, each correctly decoding relay transmits one bit "1" to the source with channel inversion, i.e., compensating the channel effect before transmission so that the source can decode the transmitted bits without CSI. Only relays that can decode the received data successfully (i.e., can support rate R with P_{max}) perform channel inversion. This is known as truncated channel inversion that leads to finite average transmission power [108]. After the M correctly decoding relays each transmit a "1" message to the source, they switch to idle mode waiting for expiration of their timers and are also able to receive and process signals. The source adds the received bits up to obtain the number of correctly decoding relays (M), and then based on M determines the optimal number of relays to be selected (K) that maximizes EE (see Section 3.5). In practice, signals are transmitted in data packets with preambles and headers so that the energy consumption for signalling M to the source is higher. However, as it will be shown in Section 3.5 for some packet lengths the optimal number of selected relays K is independent of M and hence source does not need this information.

The overall relay transmission power for signalling the size of the decoding relay set, $M = |\mathscr{D}|$, to the source is given by

$$P_M = N_0 B(2^R - 1) \sum_{j=1}^{M} \frac{1}{h_j}. \tag{3.4}$$

Each correctly decoding relay starts a timer once they have transmitted the one bit "1" as follows

$$t_{j:M} = \left\lfloor \frac{\tilde{\lambda}}{g_{j:M} \Delta_g} \right\rfloor \Delta_g, \quad j \in \mathscr{D}, \quad g_{1:M} > g_{2:M} > \ldots > g_{M:M}, \tag{3.5}$$

where $\tilde{\lambda} = \overline{g}\lambda$, λ is a predefined constant parameter, and Δ_g is a guard interval that depends on the processing delay, the propagation delay, and the transmitted symbol duration [35]. For the proposed scheme we set $\Delta_g = N_T T_S$, where N_T and T_S are the number of symbols used for training and the symbol duration, respectively. The processing delay and the propagation delay are negligible compared to the symbol duration. The correctly decoding relays are ranked in descending order of their channel strengths to the destination so that the timer of the relay with the strongest channel in the second hop expires first, followed by the timer of the relay with the second strongest second-hop channel and so on.

Proposition 1

The time required for selecting the K best relays is obtained as

$$T_{sel,K} = \Delta_g \frac{M!}{(K-1)!} \sum_{n=1}^{n_{max}} \sum_{i=0}^{M-K} \frac{(-1)^i n}{(i+K)(M-i-K)!i!} \left(\exp\left(-\frac{i+K}{n+1}\theta\right) - \exp\left(-\frac{i+K}{n}\theta\right) \right), \tag{3.6}$$

where $\theta = \frac{\lambda}{\Delta_g}$, $n_{max} = \left\lfloor \frac{T_{max}}{\Delta_g} \right\rfloor$, and T_{max} is the maximum allowable relay selection time.

Proof. Probability density function (pdf) for the K-th best channel power gain $g_{K:M}$ is given by [109]

$$p_{g_{K:M}}(x) = \frac{M!}{\overline{g}(K-1)!} \sum_{i=0}^{M-K} \frac{(-1)^i}{(M-K-i)!i!} \exp\left(-\frac{i+K}{\overline{g}}x\right). \tag{3.7}$$

It follows then for the average relay selection time

$$T_{sel,K} = \Delta_g \mathbb{E}\left\{ \left\lfloor \frac{\tilde{\lambda}}{g_{K:M}\Delta_g} \right\rfloor \right\} = \Delta_g \sum_{n=1}^{n_{max}} nPr\left\{ \frac{\tilde{\lambda}}{(n+1)\Delta_g} \leq g_{K:M} \leq \frac{\tilde{\lambda}}{n\Delta_g} \right\} = \Delta_g \sum_{n=1}^{n_{max}} n \int_{\tilde{\lambda}/(n+1)\Delta_g}^{\tilde{\lambda}/n\Delta_g} p_{g_{K:M}}(x)dx = \Delta_g \frac{M!}{\overline{g}(K-1)!} \sum_{n=1}^{n_{max}} \sum_{i=0}^{M-K} \frac{(-1)^i n}{(M-K-i)!i!} \int_{\tilde{\lambda}/(n+1)\Delta_g}^{\tilde{\lambda}/n\Delta_g} \exp\left(-\frac{i+K}{\overline{g}}x\right) dx. \tag{3.8}$$

Evaluation of the integral in (3.8) leads to (3.6). □

Step 2: After the expiration of its timer, a relay transmits N_T training symbols with transmission power of

$$P_T^R = \max\left\{ P_T^S, P_T^D \right\}. \tag{3.9}$$

In this way, by exploiting the broadcast nature of the wireless channel, the source and the destination can use the same training symbols to perform channel estimation and obtain the corresponding CSI. The source will use the estimated first-hop CSI to adapt its data transmission power to the minimum level required for reaching the selected relays (see Section 3.1.3).

Due to the use of discrete relay timers in (3.5), collisions between relay transmissions may occur if the timers of two or more relays expire at the same time.

Proposition 2

The collision probabilities among the K best relays for $K = 1$ and $K > 1$ are given by

$$p_{coll,K=1,n_{max}} = 1 - M \sum_{n=0}^{n_{max}} \left(\exp\left(-\frac{\theta}{n+1}\right) - \exp\left(-\frac{\theta}{n}\right) \right) \left(1 - \exp\left(-\frac{\theta}{n+1}\right) \right)^{M-1}, \tag{3.10}$$

$$p_{coll,K>1,n_{max}} = 1 - \frac{M!}{(M-K)!(K-1)!} \sum_{n=K-1}^{n_{max}} \exp\left(-\frac{(K-1)\theta}{n}\right)$$
$$\left(\exp\left(-\frac{\theta}{n+1}\right) - \exp\left(-\frac{\theta}{n}\right)\right)\left(1-\exp\left(-\frac{\theta}{n+1}\right)\right)^{M-K}\left(1 - I_{\{K\geq 3\}}(K)p_{coll,K-2,n}\right), \tag{3.11}$$

where $p_{no-coll,K,n_{max}}$ is the probability that no collision occurs, and the indicator function $I_{\mathbb{A}}(x) = 1$ if $x \in \mathbb{A}$, 0 otherwise.

Proof. Let $\mathscr{K}$ be the set containing $(K-1)$ best relays and $\mathscr{R} = \mathscr{D} \setminus (\mathscr{K} \cup \{j\})$. For collision-free K best relay selection, the following conditions have to be satisfied: (1) for $(K-1)$ best relays $\tilde{\lambda}/g_{i\in\mathscr{K}} < n\Delta_g$ and no collisions between relays in this interval, (2) for the Kth best relay $n\Delta_g \leq \tilde{\lambda}/g_{j\neq i} < (n+1)\Delta_g$, and (3) for the remaining $(M-K)$ relays $\tilde{\lambda}/g_{r\in\mathscr{R}} \geq (n+1)\Delta_g$. For the best relay selection ($K=1$) only conditions (2) and (3) are relevant.

Using multinomial distribution, the probability that all the three conditions (for $K > 1$) are fulfilled is given by

$$p_{no-coll,K>1,n_{max}} = \frac{M!}{(M-K)!(K-1)!} \sum_{n=K-1}^{n_{max}} \left(\prod_{i\in\mathscr{K}} Pr\{\tilde{\lambda}/g_i < n\Delta_g\}\right)$$
$$Pr\{n\Delta_g \leq \tilde{\lambda}/g_{j\neq i} < (n+1)\Delta_g\}\left(\prod_{r\in\mathscr{R}} Pr\{\tilde{\lambda}/g_r \geq (n+1)\Delta_g\}\right)$$
$$\left(1 - I_{\{K\geq 3\}}(K)p_{coll,K-2,n}\right) = \frac{M!}{(M-K)!(K-1)!} \sum_{n=K-1}^{n_{max}} \left(1 - F_g(\tilde{\lambda}/n\Delta_g)\right)^{K-1}$$
$$\left(F_g(\tilde{\lambda}/n\Delta_g) - F_g(\tilde{\lambda}/(n+1)\Delta_g)\right)F_g^{M-K}(\tilde{\lambda}/(n+1)\Delta_g)\left(1 - I_{\{K\geq 3\}}(K)p_{coll,K-2,n}\right), \tag{3.12}$$

while the probability that only conditions (2) and (3) are satisfied for best relay selection ($K=1$) can be calculated as follows

$$p_{no-coll,K=1,n_{max}} = M\sum_{n=0}^{n_{max}} \left(F_g(\tilde{\lambda}/n\Delta_g) - F_g(\tilde{\lambda}/(n+1)\Delta_g)\right)F_g^{M-1}(\tilde{\lambda}/(n+1)\Delta_g), \tag{3.13}$$

where $F_g(x) = 1 - \exp(-x/\overline{g})$ is cumulative distribution function (cdf) of channel power gain g. The collision probability can be calculated using $p_{coll,K,n_{max}} = 1 - p_{no-coll,K,n_{max}}$. □

Step 3: Once the source has received training symbols from the first K relays, it informs the other $M-K$ relays via a single bit "0" to stop their timers, not to transmit training symbols, and not to participate in the immediate data transmission phase. As the source does not know CSI of all M correctly decoding relays and the channel remains the same within channel coherence time, the M-K relays should be able to correctly decode the single bit notification from the source as long as the source transmits with maximum allowed power P_{max}. It is assumed that the relay with timer $t_{K+1:M}$ receives the single bit "0" notification before it starts transmitting training symbols, given that the propagation delay is negligible compared to the guard interval.

Prior to data transmission, the destination broadcasts the sum of the K estimated second-hop channel power gains, which will be used by the selected K relays for cooperative beamforming with the optimal transmission power, using the following transmission power

$$P_{FB} = \frac{N_0 B(2^R - 1)}{g_{K:M}}, \tag{3.14}$$

where the weakest second-hop channel power gain $g_{K:M}$ among the K selected relays is used, because this broadcast information has to reach all the K selected relays.

3.1.3 Data Transmission Phase

So far, the source and the K selected relays have obtained all necessary information to perform data transmission in an energy-efficient manner. In the first hop, the source transmits data with the minimum transmission power required for reaching the K selected relays, i.e.,

$$P_{AD} = \frac{N_0 B(2^R - 1)}{\min\{h_1, \ldots, h_K\}}. \tag{3.15}$$

To some extent, this may also prevent the other $M-K$ relays from unnecessarily decoding and buffering data packets.

In the second hop, the K selected DF relays perform cooperative beamforming to transmit the decoded source data to the destination, with the overall transmission power given by

$$P_{CB} = \sum_{i=1}^{K} P_{CB}^{i}, \tag{3.16}$$

where P_{CB}^{i} is the optimal transmission power at relay i and as shown in Appendix A.1 is calculated as follows

$$P_{CB}^{i} = N_0 B(2^R - 1)\left(\frac{1}{\sqrt{g_{i:M}}}\sum_{j=1}^{K} g_{j:M}\right)^{-2}. \tag{3.17}$$

The minimum channel coherence time required for the proposed cooperative relaying scheme is given by

$$T_{min-coh} = ((K+2)N_T + (M+1)/R + N_{FB} + 2N_D)\,T_S + T_{sel,K}. \tag{3.18}$$

where N_{FB} is the number of symbols used for destination feedback, and N_D is the number of symbols per data packet. The first part in the summation represents the time needed for training. The second part is the total time consumed for signalling the size of decoding set M to the source and for invalidating relay timers of not selected relays. The third and fourth parts embody the time required for destination feeding back the sum of second-hop channel power gains to the K selected relays and the time needed for cooperative data transmission, respectively. The last part is the time for selecting K relays (3.6).

3.2 Analysis of Average Energy Efficiency

In this section, the average EE under maximum transmit power constraint, P_{max}, is analysed for both cooperative communications and direct transmission, facilitating a quantitative comparison between them. EE (in bits/Joule) is defined as the ratio of the number of successfully transmitted data bits to the corresponding energy consumption.

3.2.1 Cooperative Communications

Without loss of generality, we assume that $M \geq 2$ relays decode correctly the data transmitted from the source and that $\{h_i\}_{i=1}^{M}$ and $\{g_i\}_{i=1}^{M}$ are independent and identically distributed (i.i.d), i.e., $\overline{h_i} = \overline{h}$ and $\overline{g_i} = \overline{g}$ $(i = 1, \ldots, M)$. The average EE of the proposed cooperative relaying scheme is given by

$$\overline{EE}_{CC}(K,M,\psi) = (1-p_{out}^{CC})(1-p_{coll,K,n_{max}})RN_D\mathbb{E}\left\{\frac{1}{E_O(K,M,\psi)+E_D(K,M,\psi)}\right\}$$
$$\approx \frac{(1-p_{out}^{CC})(1-p_{coll,K,n_{max}})RN_D}{\mathbb{E}\{E_O(K,M,\psi)\}+\mathbb{E}\{E_D(K,M,\psi)\}}, \tag{3.19}$$

where the second line is obtained using the first-order Taylor approximation, ψ is the location of the K selected cooperating relays, p_{out}^{CC} is the outage probability of cooperative communications, $E_O(.)$ denotes the energy consumption caused by signalling overhead, and $E_D(.)$ is the energy consumed for data transmission.

Proposition 3

The outage probability is given by

$$p_{out}^{CC} = \frac{M!}{(K-1)!}\sum_{j=0}^{M-K}(-1)^j\frac{\left(1-\exp\left(-\frac{j+K}{\bar{g}}\mu\right)\right)}{(j+K)(M-K-j)!j!}, \tag{3.20}$$

where $\mu = N_0B(2^R-1)/P_{max}$.

Proof. As it is assumed that $M \geq 2$, outage occurs only in the second hop. For the best relay selection ($K=1$), outage is declared if channel power gain $g_{1:M}$ cannot support the target rate R under maximum transmission power constraint, P_{max}. For cooperative beamforming ($K \geq 2$) outage occurs if the destination transmit power to feedback the sum of second-hop channel power gains does not meet the target rate R with P_{max}. It follows then for the outage probability

$$p_{out}^{CC} = I_{\{K=1\}}(K)Pr\{g_{1:M}<\mu\}+I_{\{2\leq K\leq M\}}(K)Pr\{g_{K:M}<\mu\} = \int_0^{\mu} p_{g_{K:M}}(x)dx$$
$$= \frac{M!}{\bar{g}(K-1)!}\sum_{j=0}^{M-K}\frac{(-1)^j}{(M-K-j)!j!}\int_0^{\mu}\exp\left(-\frac{j+K}{\bar{g}}x\right)dx. \tag{3.21}$$

Evaluation of integral in (3.21) leads to (3.20). □

In (3.19), $E_O(.)$ is the total energy consumed for training $E_T(.)$, for destination feedback $E_{FB}(.)$, for relays signalling M to source $E_M(.)$, and for source telling non-selected relays to invalidate their timers E_{INV}.

Proposition 4

The average energy consumption for the signalling overhead is given by

$$\begin{aligned}\mathbb{E}\{E_O(K,M,\psi)\} &= E_T(K,M,\psi) + E_{INV} \\ &+ I_{\{2\leq K\leq M\}}(K)\mathbb{E}\{E_{FB}(K,M,\psi)\} + \mathbb{E}\{E_M(M,\psi)\},\end{aligned} \tag{3.22}$$

where

$$E_T(K,M,\psi) = N_T N_0 B T_S \left(\frac{1-2^R}{\ln(1-\delta_{out})}\right)\left(\frac{1}{\overline{h}} + \frac{1}{\overline{g}} + K\max\left(\frac{1}{\overline{h}}, \frac{1}{\overline{g}}\right)\right), \tag{3.23}$$

$$E_{INV} = N_{INV} T_S P_{max}, \tag{3.24}$$

$$\begin{aligned}&\mathbb{E}\{E_{FB}(K,M,\psi)\} \\ &= -N_{FB} T_S N_0 B(2^R-1)\frac{M!}{\overline{g}(K-1)!}\left(\sum_{j=0}^{M-K}\frac{(-1)^j}{(M-K-j)!j!}Ei\left(-\frac{j+K}{\overline{g}}\mu\right)\right) \\ &\left(1-\frac{M!}{(K-1)!}\sum_{j=0}^{M-K}\frac{(-1)^j}{(M-K-j)!j!(j+K)}\left(1-\exp\left(-\frac{j+K}{\overline{g}}\mu\right)\right)\right)^{-1},\end{aligned} \tag{3.25}$$

$$\mathbb{E}\{E_M(M,\psi)\} = -M\frac{N_M T_S N_0 B(2^R-1)}{\overline{h}}\exp\left(\frac{\mu}{\overline{h}}\right)Ei\left(-\frac{\mu}{\overline{h}}\right), \tag{3.26}$$

in which N_{INV} and N_M are the numbers of symbols used for invalidating not-selected relays' timers and relays signalling M to source, respectively, and Ei is the exponential integral function, defined as $Ei(x) = \int_{-\infty}^{x}\frac{\exp(t)}{t}dt$ [110]. The overall energy consumption for the training $E_T(.)$ in (3.23) is composed of three parts. The first part is the energy consumed for transmission of N_T training symbols from the source to relays. The second part constitutes the energy consumption for sending N_T training symbols from the destination to relays. The last part represents the energy consumed for K selected relays to broadcast N_T training symbols.

Proof. Expressions (3.22)-(3.24) can be obtained easily from the Fig. 3.1 and discussions in Section 3.1.

Average energy consumption for the destination feedback is calculated as follows

$$\begin{aligned}\mathbb{E}\{E_{FB}(K,M,\psi)\} &= N_{FB}T_S N_0 B(2^R-1)\mathbb{E}\left\{\frac{1}{g_{K:M}}|g_{K:M}\geq\mu\right\}\\ &= N_{FB}T_S N_0 B(2^R-1)\int_{\mu}^{\infty}\frac{1}{x}p_{g_{K:M}}(x)dx(1-F_{g_{K:M}}(\mu))^{-1},\end{aligned} \tag{3.27}$$

where

$$\begin{aligned}\int_{\mu}^{\infty}\frac{1}{x}p_{g_{K:M}}(x)dx &= \frac{M!}{\overline{g}(K-1)!}\sum_{j=0}^{M-K}\frac{(-1)^j}{(M-K-j)!j!}\int_{\mu}^{\infty}\frac{1}{x}\exp\left(-\frac{i+K}{\overline{g}}x\right)dx\\ &= \frac{M!}{\overline{g}(K-1)!}\sum_{j=0}^{M-K}\frac{(-1)^j}{(M-K-j)!j!}Ei\left(-\frac{j+K}{\overline{g}}\mu\right),\end{aligned} \tag{3.28}$$

$$\begin{aligned}F_{g_{K:M}}(\mu) = \int_{0}^{\mu}p_{g_{K:M}}(x)dx &= \frac{M!}{\overline{g}(K-1)!}\sum_{j=0}^{M-K}\frac{(-1)^j}{(M-K-j)!j!}\int_{0}^{\mu}\exp\left(-\frac{j+K}{\overline{g}}x\right)dx\\ &= \frac{M!}{(K-1)!}\sum_{j=0}^{M-K}\frac{(-1)^j}{(j+K)(M-K-j)!j!}\left(1-\exp\left(-\frac{j+K}{\overline{g}}\mu\right)\right).\end{aligned} \tag{3.29}$$

$F_{g_{K:M}}(\mu)$ denotes cdf of $g_{K:M}$.

Average energy consumed to signal M to the source is given by

$$\begin{aligned}\mathbb{E}\{E_M(M,\psi)\} &= N_M T_S N_0 B(2^R-1)\sum_{i=1}^{M}\mathbb{E}\left\{\frac{1}{h_i}|h_i\geq\mu\right\}\\ &= N_M T_S N_0 B(2^R-1)\sum_{i=1}^{M}\int_{\mu}^{\infty}\frac{1}{x}p_{h_i}(x)dx\,(1-F_{h_i}(\mu))^{-1},\end{aligned} \tag{3.30}$$

where

$$\int_{\mu}^{\infty}\frac{1}{x}p_{h_i}(x)dx = \frac{1}{\overline{h}}\int_{\mu}^{\infty}\frac{1}{x}\exp\left(-\frac{x}{\overline{h}}\right)dx = -\frac{1}{\overline{h}}Ei\left(-\frac{\mu}{\overline{h}}\right), \tag{3.31}$$

$$F_{h_i}(\mu) = \int_{0}^{\mu}\frac{1}{\overline{h}}\exp\left(-\frac{x}{\overline{h}}\right)dx = 1-\exp\left(-\frac{\mu}{\overline{h}}\right). \tag{3.32}$$

□

The energy consumption for data transmission, $E_D(.)$, comprises the energy consumed in the first hop $E_D^I(.)$ and that in the second hop $E_D^{II}(.)$.

Proposition 5

The average energy consumption for the data transmission is given by

$$\mathbb{E}\{E_D(K,M,\psi)\} = \mathbb{E}\{E_D^I(K,M,\psi)\} + I_{\{K=1\}}(K)\mathbb{E}\{E_D^{II}(K=1,M,\psi)\} \\ + I_{\{2\leq K\leq M\}}(K)\mathbb{E}\{E_D^{II}(K>1,M,\psi)\}. \tag{3.33}$$

where

$$\mathbb{E}\{E_D^I(K,M,\psi)\} = -K\frac{N_D T_S N_0 B(2^R-1)}{\bar{h}}\exp\left(\frac{K}{\bar{h}}\mu\right)Ei\left(-\frac{K}{\bar{h}}\mu\right), \tag{3.34}$$

$$\mathbb{E}\{E_D^{II}(K=1,M,\psi)\} = -N_D T_S N_0 B(2^R-1)\frac{M!}{\bar{g}}\left(\sum_{j=0}^{M-1}\frac{(-1)^j}{(M-j-1)!j!}Ei\left(-\frac{j+1}{\bar{g}}\mu\right)\right) \\ \left(1-M!\sum_{j=0}^{M-1}\frac{(-1)^j}{(M-j-1)!(j+1)!}\left(1-\exp\left(-\frac{j+1}{\bar{g}}\mu\right)\right)\right)^{-1}, \tag{3.35}$$

$$\mathbb{E}\{E_D^{II}(K>1,M,\psi)\} = \frac{N_D T_S N_0 B(2^R-1)}{\bar{g}}\binom{M}{K}\left(\frac{\Gamma\left(K-1,K\frac{\mu}{\bar{g}}\right)}{(K-1)!}+\sum_{i=1}^{M-K}(-1)^{i+K-1}\right. \\ \left.\binom{M-K}{i}\left(\frac{K}{i}\right)^{K-1}\left(Ei\left(-K\frac{\mu}{\bar{g}}\right)-Ei\left(-\left(K+i\right)\frac{\mu}{\bar{g}}\right)-\sum_{j=1}^{K-2}\frac{\left(-\frac{i}{K}\right)^j}{j!}\Gamma\left(j,K\frac{\mu}{\bar{g}}\right)\right)\right) \\ \left(1-\frac{M!}{(K-1)!}\sum_{j=0}^{M-K}\frac{(-1)^j}{(j+K)(M-K-j)!j!}\left(1-\exp\left(-\frac{j+K}{\bar{g}}\mu\right)\right)\right)^{-1}, \tag{3.36}$$

with $\Gamma(\alpha,x) = \int_x^\infty t^{\alpha-1}\exp(-t)dt$ being the upper incomplete gamma function [110].

Proof. Summation of the average energy consumption for the first and second hop data transmission as well as considering both cases best relay selection ($K=1$) and cooperative beamforming ($K\geq 2$) leads to (3.33).

The average energy consumption for data transmission from the source to the K selected relays is given by

$$\mathbb{E}\{E_D^I(K,M,\psi)\} = N_D T_S N_0 B(2^R-1)\mathbb{E}\left\{\frac{1}{\mathscr{H}_{min}}|\mathscr{H}_{min} \geq \mu\right\}$$
$$= N_D T_S N_0 B(2^R-1)\int_{\mu}^{\infty}\frac{1}{x}p_{\mathscr{H}_{min}}(x)dx(1-F_{\mathscr{H}_{min}}(\mu))^{-1}, \tag{3.37}$$

where $\mathscr{H}_{min} = \min\{h_1,\ldots,h_K\}$ and [109]

$$p_{\mathscr{H}_{min}}(x) = \frac{K}{\overline{g}}\exp\left(-\frac{K}{\overline{g}}x\right), \tag{3.38}$$

It follows then

$$\int_{\mu}^{\infty}\frac{1}{x}p_{\mathscr{H}_{min}}(x)dx = \frac{K}{\overline{h}}\int_{\mu}^{\infty}\frac{1}{x}\exp\left(-\frac{K}{\overline{h}}x\right)dx = -\frac{K}{\overline{h}}\int_{-\infty}^{-K\mu/\overline{h}}\frac{exp(t)}{t}dt = Ei\left(-\frac{K}{\overline{h}}\mu\right), \tag{3.39}$$

$$F_{\mathscr{H}_{min}}(\mu) = \frac{K}{\overline{h}}\int_{\mu}^{\infty}\exp\left(-\frac{K}{\overline{h}}x\right)dx = \frac{K}{\overline{h}}\exp\left(-\frac{K}{\overline{h}}\mu\right). \tag{3.40}$$

Substitution (3.39) and (3.40) in (3.37) leads to (3.34).

Average energy consumed in the second hop for the data transmission for the best relay selection ($K=1$) can be calculated as follows

$$\mathbb{E}\{E_D^{II}(K=1,M,\psi)\} = N_D T_S N_0 B(2^R-1)\mathbb{E}\left\{\frac{1}{g_{1:M}}|g_{1:M} \geq \mu\right\}$$
$$= N_D T_S N_0 B(2^R-1)\int_{\mu}^{\infty}\frac{1}{x}p_{g_{1:M}}(x)dx(1-F_{g_{1:M}}(\mu))^{-1}, \tag{3.41}$$

where

$$\int_{\mu K}^{\infty}\frac{1}{x}p_{g_{1:M}}(x)dx = \frac{M!}{\overline{g}}\sum_{j=0}^{M-1}\frac{(-1)^j}{(M-j-1)!j!}\int_{\mu K}^{\infty}\frac{1}{x}\exp\left(-\frac{j+1}{\overline{g}}x\right)dx$$
$$= \frac{M!}{\overline{g}}\sum_{j=0}^{M-1}\frac{(-1)^j}{(M-j-1)!j!}Ei\left(-\frac{j+1}{\overline{g}}\mu\right), \tag{3.42}$$

$$
\begin{aligned}
F_{g_{1:M}}(\mu) &= \frac{M!}{\overline{g}} \sum_{j=0}^{M-1} \frac{(-1)^j}{(M-j-1)!j!} \int_0^{\mu} \exp\left(-\frac{j+1}{\overline{g}}x\right) dx \\
&= M! \sum_{j=0}^{M-1} \frac{(-1)^j}{(M-j-1)!(j+1)!} \left(1-\exp\left(-\frac{j+1}{\overline{g}}\mu\right)\right).
\end{aligned} \tag{3.43}
$$

Average energy consumed in the second hop for the data transmission for cooperative beamforming ($K \geq 2$) is given by

$$
\begin{aligned}
\mathbb{E}\{E_D^{II}(K>1,M,\psi)\} &= N_D T_S N_0 B(2^R-1)\mathbb{E}\left\{\frac{1}{\sum_{i=1}^{K} g_{i:M}} | g_{K:M} \geq \mu\right\} \\
&= N_D T_S N_0 B(2^R-1) \int_{\mu K}^{\infty} \frac{1}{x} p_{\sum_{i=1}^{K} g_{i:M}}(x) dx (1-F_{g_{K:M}}(\mu))^{-1}.
\end{aligned} \tag{3.44}
$$

Calculation of $p_{\sum_{i=1}^{K} g_{i:M}}(x)$ can be simplified using statistical independence property of spacings between consecutive exponentially distributed ordered random variables [111].

Let $d_m = g_{m:M} - g_{m+1:M}$, $1 \leq m \leq M$, be spacing between two adjacent ordered random variables, then

$$
\begin{aligned}
g_{M:M} &= d_M, \\
g_{M-1:M} &= d_M + d_{M-1}, \\
&\vdots \\
g_{K:M} &= d_M + d_{M-1} + \cdots + d_K, \\
&\vdots \\
g_{1:M} &= d_M + d_{M-1} + \cdots + d_K + \cdots + d_1,
\end{aligned}
$$

and for the sum of K largest channel power gains

$$
\sum_{i=1}^{K} g_{i:M} = \sum_{j=1}^{K} j d_j + K \sum_{j=K+1}^{M} d_j. \tag{3.45}
$$

Spacing pdf is given by [111]

$$
p_{d_m}(x) = \frac{m}{\overline{g}} \exp\left(-m\frac{x}{\overline{g}}\right), \; x \geq 0. \tag{3.46}
$$

It follows for moment generating function (MGF)

$$
\begin{aligned}
&\mathscr{M}_{\sum_{i=1}^{K} g_{i:M}}(s) \\
&= (1-\overline{g}s)^{-K} \prod_{j=K+1}^{M} \left(1-\frac{\overline{g}K}{j}s\right)^{-1} = \left(\frac{1}{(1-\overline{g}s)^{K}}\right) \prod_{j=K+1}^{M} \left(-\frac{j}{\overline{g}K}\right) \left(\frac{1}{s-j/\overline{g}K}\right) \\
&= (-1)^{M-K}\frac{M!}{K!}\left(\frac{1}{\overline{g}K}\right)^{M-K}\left(\frac{1}{(1-\overline{g}s)^{K}}\right) \prod_{j=K+1}^{M}\left(\frac{1}{s-j/\overline{g}K}\right).
\end{aligned}
\tag{3.47}
$$

Using partial fraction for simple roots (see Appendix A.2) leads to

$$
\begin{aligned}
&\mathscr{M}_{\sum_{i=1}^{K} g_{i:M}}(s) = (-1)^{M-K}\frac{M!}{K!}\left(\frac{1}{\overline{g}K}\right)^{M-K}\left(\frac{1}{(1-\overline{g}s)^{K}}\right) \sum_{j=K+1}^{M}\left(\prod_{\substack{i=K+1\\ i\neq j}}^{M}\frac{\overline{g}K}{j-i}\right)\left(\frac{1}{s-j/\overline{g}K}\right) \\
&= (-1)^{M-K}\frac{M!}{K!}(\overline{g}K)^{K-M}\frac{(\overline{g}K)^{M-K-1}}{(1-\overline{g}s)^{K}} \sum_{j=K+1}^{M}\left(\prod_{\substack{i=K+1\\ i\neq j}}^{M}\frac{1}{j-i}\right)\left(\frac{1}{s-j/\overline{g}K}\right) \\
&= (-1)^{M-K}\frac{M!}{K!}\left(\frac{1}{\overline{g}K(1-\overline{g}s)^{K}}\right) \sum_{j=K+1}^{M}\left(\prod_{i=K+1}^{j-1}\frac{1}{j-i}\prod_{i=j+1}^{M}\frac{1}{j-i}\right)\left(\frac{1}{s-j/\overline{g}K}\right) \\
&= \left(\frac{M!}{KK!\overline{g}(1-\overline{g}s)^{K}}\right) \sum_{j=K+1}^{M}\frac{(-1)^{j+K}}{(j-K-1)!(M-j)!}\left(\frac{1}{s-j/\overline{g}K}\right).
\end{aligned}
\tag{3.48}
$$

The pdf of $\sum_{i=1}^{K} g_{i:M}$ can be computed as follows

$$
\begin{aligned}
&p_{\sum_{i=1}^{K} g_{i:M}}(x) = \mathscr{L}^{-1}\left\{\mathscr{M}_{\sum_{i=1}^{K} g_{i:M}}(-s)\right\} \\
&= \frac{M!}{KK!\overline{g}^{K+1}} \sum_{j=K+1}^{M}\frac{(-1)^{j+K-1}}{(j-K-1)!(M-j)!}\mathscr{L}^{-1}\left\{\left(s+\frac{1}{\overline{g}}\right)^{-K}\right\} * \mathscr{L}^{-1}\left\{\left(s+\frac{j}{\overline{g}K}\right)^{-1}\right\},
\end{aligned}
\tag{3.49}
$$

where $\mathscr{L}^{-1}$ is inverse Laplace transformation and '*' denotes convolution operator. Using Laplace transform table [110] and performing convolution leads to

$$
\begin{aligned}
&p_{\sum_{i=1}^{K} g_{i:M}}(x) = \mathscr{L}^{-1}\left\{\mathscr{M}_{\sum_{i=1}^{K} g_{i:M}}(-s)\right\} \\
&= \frac{M!}{KK!\overline{g}^{K+1}} \sum_{j=K+1}^{M}\frac{(-1)^{j+K-1}}{(j-K-1)!(M-j)!}\left(\frac{1}{(K-1)!}x^{K-1}\exp\left(-\frac{x}{\overline{g}}\right) * \exp\left(-\frac{jx}{\overline{g}K}\right)\right)
\end{aligned}
$$

$$= \frac{M!}{KK!\overline{g}^{K+1}} \sum_{j=K+1}^{M} \frac{(-1)^{j+K-1}}{(j-K-1)!(M-j)!} \exp\left(-\frac{jx}{\overline{g}K}\right) \int_0^x y^{K-1} \exp\left(-\left(1-\frac{j}{K}\right)\frac{y}{\overline{g}}\right) dy$$
$$= \frac{M!}{KK!\overline{g}} \sum_{j=K+1}^{M} \frac{(-1)^{j+K-1}}{(j-K-1)!(M-j)!} \left(\frac{K}{K-j}\right)^K \exp\left(-\frac{jx}{\overline{g}K}\right) \gamma\left(K, \left(1-\frac{j}{K}\right)\frac{x}{\overline{g}}\right), \tag{3.50}$$

where $\gamma(\alpha, x) = \int_0^x t^{\alpha-1}\exp(-t)dt$ is the lower incomplete gamma function and for the special case above is [110]

$$\gamma\left(K, \left(1-\frac{j}{K}\right)\frac{x}{\overline{g}}\right) = (K-1)!\left(1 - \exp\left(-\left(1-\frac{j}{K}\right)\frac{x}{\overline{g}}\right)\sum_{k=0}^{K-1} \frac{\left(\left(1-\frac{j}{K}\right)\frac{x}{\overline{g}}\right)^k}{k!}\right). \tag{3.51}$$

Insertion of (3.51) in (3.50) and substitution $i = j - K$ yields

$$p_{\sum_{i=1}^K g_{i:M}}(x) = \frac{M!}{K!(M-K)!\overline{g}} \sum_{i=1}^{M-K} \frac{(-1)^{i+K-1}(M-K)!}{i!(M-K-i)!} \left(\frac{K}{i}\right)^{K-1} \exp\left(-\frac{x}{\overline{g}}\right)$$
$$\left(\exp\left(-\frac{ix}{K\overline{g}}\right) - \sum_{k=0}^{K-1}\left(-\frac{ix}{K\overline{g}}\right)^k \frac{1}{k!}\right) = \frac{M!\exp\left(-\frac{x}{\overline{g}}\right)}{K!(M-K)!\overline{g}} \sum_{i=1}^{M-K} (-1)^{i+K-1} \binom{M-K}{i}$$
$$\left(\frac{K}{i}\right)^{K-1} \left(\exp\left(-\frac{ix}{K\overline{g}}\right) + (-1)^K \left(\frac{ix}{K\overline{g}}\right)^{K-1} \frac{1}{(K-1)!} \sum_{k=0}^{K-2}\left(-\frac{ix}{K\overline{g}}\right)^k \frac{1}{k!}\right)$$
$$= \frac{M!\exp\left(-\frac{x}{\overline{g}}\right)}{K!(M-K)!\overline{g}} \sum_{i=1}^{M-K} (-1)^{i-1} \binom{M-K}{i} \left(\frac{K}{i}\right)^{K-1} \left(\frac{ix}{K\overline{g}}\right)^{K-1} \frac{1}{(K-1)!} + \frac{M!\exp\left(-\frac{x}{\overline{g}}\right)}{K!(M-K)!\overline{g}}$$
$$\sum_{i=1}^{M-K} (-1)^{i+K-1} \binom{M-K}{i} \left(\frac{K}{i}\right)^{K-1} \left(\exp\left(-\frac{ix}{K\overline{g}}\right) - \sum_{k=0}^{K-2}\left(-\frac{ix}{K\overline{g}}\right)^k \frac{1}{k!}\right)$$
$$= \frac{M!}{(M-K)!K!} \exp\left(-\frac{x}{\overline{g}}\right) \left(\sum_{i=1}^{M-K} (-1)^{i-1} \binom{M-K}{i} \frac{x^{K-1}}{\overline{g}^K (K-1)!}\right.$$
$$\left. + \frac{1}{\overline{g}} \sum_{i=1}^{M-K} (-1)^{i+K-1} \frac{(M-K)!}{(M-K-i)!i!} \left(\frac{K}{i}\right)^{K-1} \left(\exp\left(-\frac{ix}{K\overline{g}}\right) - \sum_{k=0}^{K-2}\left(-\frac{ix}{K\overline{g}}\right)^k \frac{1}{k!}\right)\right). \tag{3.52}$$

For the sum of binomial coefficients holds $\sum_{k=0}^{m}(-1)^k\begin{pmatrix} m \\ k \end{pmatrix}=0$ [110], i.e.,

$$\sum_{i=1}^{M-K}(-1)^{i-1}\begin{pmatrix} M-K \\ i \end{pmatrix}=1. \tag{3.53}$$

Using (3.53) in (3.52) gives

$$p_{\sum_{i=1}^{K} g_{i:M}}(x)=\frac{M!}{(M-K)!K!}\exp\left(-\frac{x}{\overline{g}}\right)\left(\frac{x^{K-1}}{\overline{g}^K(K-1)!}+\frac{1}{\overline{g}}\sum_{i=1}^{M-K}(-1)^{i+K-1}\frac{(M-K)!}{(M-K-i)!i!}\right.$$
$$\left.\left(\frac{K}{i}\right)^{K-1}\left(\exp\left(-\frac{ix}{K\overline{g}}\right)-\sum_{k=0}^{K-2}\left(-\frac{ix}{K\overline{g}}\right)^k\frac{1}{k!}\right)\right). \tag{3.54}$$

It follows then

$$\int_{\mu K}^{\infty}\frac{1}{x}p_{\sum_{i=1}^{K} g_{i:M}}(x)dx=\frac{M!}{(M-K)!K!}\left(\frac{1}{\overline{g}^K(K-1)!}\int_{\mu K}^{\infty}x^{K-2}\exp\left(-\frac{x}{\overline{g}}\right)dx\right.$$
$$+\frac{1}{\overline{g}}\sum_{i=1}^{M-K}(-1)^{i+K-1}\frac{(M-K)!}{(M-K-i)!i!}\left(\frac{K}{i}\right)^{K-1}\left(\int_{\mu K}^{\infty}\frac{1}{x}\exp\left(-\left(1+\frac{i}{K}\right)\frac{x}{\overline{g}}\right)dx\right.$$
$$\left.\left.-\int_{\mu K}^{\infty}\frac{1}{x}\exp\left(-\frac{x}{\overline{g}}\right)dx-\sum_{k=1}^{K-2}\frac{1}{k!}\left(-\frac{i}{K\overline{g}}\right)^k\int_{\mu K}^{\infty}x^{k-1}\exp\left(-\frac{x}{\overline{g}}\right)dx\right)\right), \tag{3.55}$$

where [110]

$$\int_{\mu K}^{\infty}x^{K-2}\exp\left(-\frac{x}{\overline{g}}\right)dx=\overline{g}^{K-1}\Gamma\left(K-1,\frac{K}{\overline{g}}\mu\right), \tag{3.56}$$

$$\int_{\mu K}^{\infty}\frac{1}{x}\exp\left(-\left(1+\frac{i}{K}\right)\frac{x}{\overline{g}}\right)dx=-Ei\left(-\left(1+\frac{i}{K}\right)\frac{K}{\overline{g}}\mu\right), \tag{3.57}$$

$$\int_{\mu K}^{\infty}\frac{1}{x}\exp\left(-\frac{x}{\overline{g}}\right)dx=-Ei\left(-\frac{K}{\overline{g}}\mu\right), \tag{3.58}$$

$$\int_{\mu K}^{\infty}x^{K-1}\exp\left(-\frac{x}{\overline{g}}\right)dx=\overline{g}^{K}\Gamma\left(K,\frac{K}{\overline{g}}\mu\right). \tag{3.59}$$

Substitution of (3.55) and (3.29) in (3.44) lead to (3.36). □

Lemma 1

The average EE in (3.19) can be upper bounded as follows

$$\overline{EE}_{CC}(K,M,\psi) \leq \overline{EE}_{CC}^{UB}(K,M,\psi) = \frac{(1-p_{out}^{CC})(1-p_{coll,K,n_{max}})RN_D}{\overline{E}_O^{LB}(K,M,\psi)+\overline{E}_D^{LB}(K,M,\psi)}, \tag{3.60}$$

where $\overline{E}_O^{LB}(K,M,\psi)$ and $\overline{E}_D^{LB}(K,M,\psi)$ denote the lower bound of average energy consumption for signalling overhead and for data transmission, respectively, and can be calculated as follows

$$\overline{E}_O^{LB}(K,M,\psi) = E_T(K,M,\psi) + \overline{E}_M^{LB}(M,\psi) + E_{INV} + I_{\{2\leq K\leq M\}}(K)\overline{E}_{FB}^{LB}(K,M,\psi), \tag{3.61}$$

$$\begin{aligned}\overline{E}_D^{LB}(K,M,\psi) = \overline{E}_D^{I,LB}(K,M,\psi) &+ I_{\{K=1\}}(K)\overline{E}_D^{II,LB}(K=1,M,\psi)\\ &+ I_{\{2\leq K\leq M\}}(K)\overline{E}_D^{II,LB}(K>1,M,\psi),\end{aligned} \tag{3.62}$$

where

$$\overline{E}_M^{LB}(M,\psi) = \frac{N_M M T_S N_0 B(2^R-1)}{\mu+\overline{h}} \exp\left(-\frac{\mu}{\overline{h}}\right), \tag{3.63}$$

$$\begin{aligned}\overline{E}_{FB}^{LB}(K,M,\psi) = N_{FB}T_S N_0 B(2^R-1)\frac{(K-1)!}{M!}\\ \left(1-\frac{M!}{(K-1)!}\sum_{j=0}^{M-K}\frac{(-1)^j}{(M-K-j)!j!(j+K)}\left(1-\exp\left(-\frac{j+K}{\overline{g}}\mu\right)\right)\right)\\ \left(\sum_{j=0}^{M-K}\frac{(-1)^j}{(M-K-j)!j!(j+K)}\exp\left(-\frac{j+K}{\overline{g}}\mu\right)\left(\mu+\frac{\overline{g}}{j+K}\right)\right)^{-1},\end{aligned} \tag{3.64}$$

$$\overline{E}_D^{I,LB}(K,M,\psi) = N_D T_S N_0 B(2^R-1)\exp\left(K\frac{\mu}{\overline{h}}\right)\left(\frac{K}{\overline{h}+\mu K}\right), \tag{3.65}$$

$$\overline{E}_D^{II,LB}(K,M,\psi) = N_D T_S N_0 B(2^R-1)$$
$$\left(\sum_{i=1}^{K}\left(1-\frac{M!}{(i-1)!}\sum_{j=0}^{M-i}\frac{(-1)^j}{(M-i-j)!j!(j+i)}\left(1-\exp\left(-\frac{j+i}{\overline{g}}\mu\right)\right)\right)\right.$$
$$\left.\left(\sum_{j=0}^{M-i}\frac{(-1)^j}{(M-i-j)!j!(j+i)}\exp\left(-\frac{j+i}{\overline{g}}\mu\right)\left(\mu+\frac{\overline{g}}{j+i}\right)\right)^{-1}\right)^{-1}. \tag{3.66}$$

Proof. Using Jensen's inequality for conditional expectations, $\mathbb{E}\left\{\frac{1}{X}|Y\right\} \geq \frac{1}{\mathbb{E}\{X|Y\}}$, where X and Y are random variables, the average energy consumption for the overhead and data transmission can be lower bounded as follows

$$\begin{aligned}
\mathbb{E}\{E_O(K,M,\psi)\} &\geq E_T(K,M,\psi) + \overline{E}_M^{LB}(M,\psi) + E_{INV} + I_{\{2\leq K\leq M\}}(K)\overline{E}_{FB}^{LB}(K,M,\psi),\\
\mathbb{E}\{E_D(K,M,\psi)\} &\geq \overline{E}_D^{I,LB}(K,M,\psi) + I_{\{K=1\}}(K)\overline{E}_D^{II,LB}(K=1,M,\psi)\\
&\quad + I_{\{2\leq K\leq M\}}(K)\overline{E}_D^{II,LB}(K>1,M,\psi),
\end{aligned}$$

where

$$\begin{aligned}
\overline{E}_M^{LB}(M,\psi) &= N_M T_S N_0 B(2^R-1)\sum_{i=1}^{M}\frac{1}{\mathbb{E}\{h_i|h_i\geq\mu\}}\\
&= N_M T_S N_0 B(2^R-1)\sum_{i=1}^{M}\left(\int_{\mu}^{\infty}\frac{x}{\overline{h}}\exp\left(-\frac{x}{\overline{h}}\right)dx\right)^{-1}\left(1-\int_{0}^{\mu}\frac{1}{\overline{h}}\exp\left(-\frac{x}{\overline{h}}\right)dx\right),
\end{aligned} \tag{3.67}$$

$$\begin{aligned}
\overline{E}_{FB}^{LB}(K,M,\psi) &= \frac{N_{FB} T_S N_0 B(2^R-1)}{\mathbb{E}\{g_{K:M}|g_{K:M}\geq\mu\}}\\
&= N_{FB} T_S N_0 B(2^R-1)\left(\frac{M!}{\overline{g}(K-1)!}\sum_{i=0}^{M-K}\frac{(-1)^i}{(M-K-i)!i!}\int_{\mu}^{\infty}x\exp\left(-\frac{i+K}{\overline{g}}x\right)dx\right)^{-1}\\
&\quad\left(1-\frac{M!}{\overline{g}(K-1)!}\sum_{i=0}^{M-K}\frac{(-1)^i}{(M-K-i)!i!}\int_{0}^{\mu}\exp\left(-\frac{i+K}{\overline{g}}x\right)dx\right),
\end{aligned} \tag{3.68}$$

$$\overline{E}_D^{I,LB}(K,M,\psi) = \frac{N_D T_S N_0 B(2^R-1)}{\mathbb{E}\{\mathscr{H}_{min}|\mathscr{H}_{min} \geq \mu\}}$$
$$= N_D T_S N_0 B(2^R-1)\left(\int_{\mu}^{\infty} \frac{Kx}{\overline{h}} \exp\left(-\frac{Kx}{\overline{h}}\right) dx\right)^{-1}\left(1-\int_{0}^{\mu} \frac{K}{\overline{h}} \exp\left(-\frac{K}{\overline{h}}\right) dx\right), \quad (3.69)$$

$$\overline{E}_D^{II,LB}(K,M,\psi) = \frac{N_D T_S N_0 B(2^R-1)}{\sum\limits_{i=1}^{K} \mathbb{E}\{g_{i:M}|g_{i:M} \geq \mu\}}$$
$$= N_D T_S N_0 B(2^R-1)\left(\sum_{i=1}^{K}\left(\frac{M!}{\overline{g}(i-1)!}\sum_{j=0}^{M-i}\frac{(-1)^j}{(M-i-j)!j!}\int_{\mu}^{\infty} x\exp\left(-\frac{j+i}{\overline{g}}x\right) dx\right)\right.$$
$$\left.\left(1-\frac{M!}{\overline{g}(i-1)!}\sum_{j=0}^{M-i}\frac{(-1)^j}{(M-i-j)!j!}\int_{0}^{\mu} \exp\left(-\frac{j+i}{\overline{g}}x\right) dx\right)^{-1}\right)^{-1}. \quad (3.70)$$

Evaluation of integrals in (3.67)-(3.70) results in (3.63)-(3.66). □

3.2.2 Direct Transmission

For EE analysis, two transmission strategies are considered for the direct communication between the source and the destination.

In the first strategy, source transmits training symbols at the minimum power required to satisfy the target R with outage probability δ_{out}, i.e.,

$$P_T^{SD} = N_0 B \frac{1-2^R}{\overline{h}_0 \ln(1-\delta_{out})}, \quad \overline{h}_0 = \left(\frac{\lambda_c}{4\pi d_0}\right)^2 \left(\frac{d_{sd}}{d_0}\right)^{-\xi}, \quad (3.71)$$

where $\overline{h}_0$ and d_{sd} denote the mean channel power gain and the distance of the direct link from source to destination, respectively. Subsequently, data is transmitted using the maximum allowed transmission power, P_{max}. The resulting average EE is given by

$$\overline{EE}_{DT}^{MAX} = (1-p_{out}^{DT})\frac{RN_D}{T_S}\left(N_T N_0 B \frac{1-2^R}{\overline{h}_0 \ln(1-\delta_{out})} + N_D P_{max}\right)^{-1}, \quad (3.72)$$

where

$$p_{out}^{DT} = Pr\{h_0 < \mu\} = \int_0^{\mu} \frac{1}{\overline{h}_0} \exp\left(-\frac{x}{\overline{h}_0}\right) dx = 1 - \exp\left(-\frac{\mu}{\overline{h}_0}\right). \tag{3.73}$$

In the second strategy, during the channel estimation phase, source sends training symbols with transmission power as in (3.71) and destination estimates the channel gain. Thereafter, the destination feedbacks CSI to the source. This enables the source to transmit data with the minimum power required to meet the target rate R. The corresponding average EE and its upper bound are given, respectively, by

$$\begin{aligned}
&\overline{EE}_{DT}^{ADP} \\
&\approx (1-p_{out}^{DT})\frac{RN_D}{T_S}\left(\frac{N_T N_0 B\left(1-2^R\right)}{\overline{h}_0 \ln(1-\delta_{out})} + (N_D+N_{FB})N_0 B\left(2^R-1\right)\mathbb{E}\left\{\frac{1}{h_0}|h_0 \geq \mu\right\}\right)^{-1} \\
&\approx \frac{(1-p_{out}^{DT})RN_D\overline{h}_0}{N_0 B T_S(1-2^R)}\left(\frac{N_T}{\ln(1-\delta_{out})} + (N_D+N_{FB})\exp\left(\frac{\mu}{\overline{h}_0}\right)Ei\left(-\frac{\mu}{\overline{h}_0}\right)\right)^{-1},
\end{aligned} \tag{3.74}$$

$$\begin{aligned}
\overline{EE}_{DT}^{ADP,UB} &= (1-p_{out}^{DT})\frac{RN_D}{T_S}\left(\frac{N_T N_0 B\left(1-2^R\right)}{\overline{h}_0 \ln(1-\delta_{out})} + \frac{(N_D+N_{FB})N_0 B\left(2^R-1\right)}{\mathbb{E}\left\{\overline{h}_0|\overline{h}_0 \geq \mu\right\}}\right)^{-1} \\
&= (1-p_{out}^{DT})\frac{RN_D}{N_0 B T_S(1-2^R)}\left(\frac{N_T}{\overline{h}_0 \ln(1-\delta_{out})} - \frac{N_D+N_{FB}}{\mu+\overline{h}_0}\right)^{-1}.
\end{aligned} \tag{3.75}$$

3.3 Optimal Location of Relays

In this section, the optimal location of cooperating relays is derived that maximizes the average EE. Without loss of generality, we assume that source is located at the origin $(0,0)$, destination is located at $(d_{sd},0)$, and the selected relays are relatively close to one another so that their distances to the source are approximately the same. Furthermore, it is assumed that diversity gains offered by relays are sufficiently high to keep the outage probability very low, i.e., $p_{out}^{CC} \approx 0$. In this case, the expressions in (3.63)-(3.66) can be simplified by replacing conditional expectations with unconditional ones. Since maximizing the average EE while maintaining the target rate R, is equivalent to minimizing the lower bound of average energy consumption, the optimal location of cooperating relays can be calculated as follows

$$\psi_{opt}(K,M) \approx \underset{\psi}{\operatorname{argmin}} \left(\overline{E}_O^{LB}(K,M,\psi) + \overline{E}_D^{LB}(K,M,\psi) \right), \tag{3.76}$$

where ψ denotes the distance from the source along the direct line connecting source and destination.

Proposition 6

The optimal position of cooperating relays is approximately given by

$$\psi_{opt}(K,M) \approx \left(1 + \left(\frac{\alpha(K,M)}{\beta(K,M)} \right)^{\frac{1}{\xi-1}} \right)^{-1} d_{sd}, \tag{3.77}$$

where

$$\frac{\alpha(K,M)}{\beta(K,M)} > 1, \quad \xi > 1,$$
$$\alpha(K,M) = \frac{M}{R} + KN_D - \frac{N_T}{\ln(1-\delta_{out})},$$

$$\beta(K,M) = I_{\{K=1\}}(K) N_D \left(\sum_{j=1}^{M} \frac{1}{j} \right)^{-1} - (1+K) \frac{N_T}{\ln(1-\delta_{out})} + I_{\{2 \le K \le M\}}(K) \left(\frac{N_D}{K} \left(1 + \sum_{j=K+1}^{M} \frac{1}{j} \right)^{-1} + N_{FB} \left(\sum_{j=K}^{M} \frac{1}{j} \right)^{-1} \right).$$

Proof. Using Lemma 1, unconditional expectations, (3.45), and (3.46) follows

$$\begin{aligned} \overline{E}_O^{LB}(K,M,\psi) &= E_T(K,M,\psi) + \overline{E}_M^{LB}(M,\psi) + E_{INV} + I_{\{2\le K\le M\}}(K)\overline{E}_{FB}^{LB}(K,M,\psi) \\ &= N_0 B T_S (2^R - 1) \left(N_M \sum_{i=1}^{M} \frac{1}{\mathbb{E}\{h_i\}} - N_T \left(\frac{1}{\ln(1-\delta_{out})} \right) \left(\frac{1}{\overline{h}} + \frac{1}{\overline{g}} + K \max\left(\frac{1}{\overline{h}}, \frac{1}{\overline{g}} \right) \right) \right. \\ &\left. + I_{\{2\le K\le M\}} N_{FB} \frac{1}{\mathbb{E}\{g_{K:M}\}} \right) + N_{INV} T_S P_{max} \end{aligned}$$

$$
\begin{aligned}
&= N_0BT_S(2^R-1)\left(N_M\frac{M}{\overline{h}} - N_T\left(\frac{1}{\ln(1-\delta_{out})}\right)\left(\frac{1}{\overline{h}}+\frac{1}{\overline{g}}+K\max\left(\frac{1}{\overline{h}},\frac{1}{\overline{g}}\right)\right)\right.\\
&\left.+I_{\{2\le K\le M\}}N_{FB}\frac{1}{\overline{g}}\left(\sum_{i=K}^{M}\frac{1}{i}\right)^{-1}\right)+N_{INV}T_SP_{max}\\
&=\left(\frac{4\pi d_0}{\lambda_c}\right)^2\frac{N_0BT_S\left(2^R-1\right)}{d_0^{\xi}}\left(\left(\frac{M}{R}-\frac{N_T}{\ln\left(1-\delta_{out}\right)}\right)\psi^{\xi}-\left(\frac{N_T}{\ln\left(1-\delta_{out}\right)}-I_{\{2\le K\le M\}}\right.\right.\\
&\left.\left.N_{FB}\left(\sum_{j=K}^{M}\frac{1}{j}\right)^{-1}\right)\left(d_{sd}-\psi\right)^{\xi}-K\frac{N_T}{\ln\left(1-\delta_{out}\right)}\max\left(\psi^{\xi},\left(d_{sd}-\psi\right)^{\xi}\right)\right)+N_{INV}T_SP_{max},
\end{aligned}
\tag{3.78}
$$

$$
\begin{aligned}
&\overline{E}_D^{LB}(K,M,\psi)\\
&=\overline{E}_D^{I,LB}(K,M,\psi)+I_{\{K=1\}}(K)\overline{E}_D^{II,LB}(K=1,M,\psi)+I_{\{2\le K\le M\}}(K)\overline{E}_D^{II,LB}(K>1,M,\psi)\\
&=N_0BN_DT_S(2^R-1)\left(\frac{1}{\mathbb{E}\{\mathscr{H}_{min}\}}+I_{\{K=1\}}(K)\frac{1}{\mathbb{E}\{g_{1:M}\}}+I_{\{2\le K\le M\}}(K)\frac{1}{\mathbb{E}\left\{\sum\limits_{j=1}^{K}g_{i:M}\right\}}\right)\\
&=N_0BT_S(2^R-1)\left(\frac{KN_D}{\overline{h}}+I_{\{K=1\}}(K)\frac{N_D}{\overline{g}}\left(\sum_{j=1}^{M}\frac{1}{j}\right)^{-1}+I_{\{2\le K\le M\}}(K)\frac{N_D}{K\overline{g}}\right.\\
&\left.\left(1+\sum_{j=K+1}^{M}\frac{1}{j}\right)^{-1}\right)=\left(\frac{4\pi d_0}{\lambda_c}\right)^2\frac{N_0BT_S\left(2^R-1\right)}{d_0^{\xi}}\left(KN_D\psi^{\xi}+\left(I_{\{K=1\}}(K)N_D\left(\sum_{j=1}^{M}\frac{1}{j}\right)^{-1}\right.\right.\\
&\left.\left.+I_{\{2\le K\le M\}}(K)\frac{N_D}{K}\left(1+\sum_{j=K+1}^{M}\frac{1}{j}\right)^{-1}\right)\left(d_{sd}-\psi\right)^{\xi}\right).
\end{aligned}
\tag{3.79}
$$

Using $\underset{x}{\operatorname{argmin}}\left(af(x)+b\right)=\underset{x}{\operatorname{argmin}}f(x)$, for constant $a>0,b$, (3.78), and (3.79), the optimization problem in (3.76) can be reformulated as

$$
\begin{aligned}
\psi_{opt}(K,M)\approx \underset{\psi}{\operatorname{argmin}}\Big(&(\mathscr{C}_T+\mathscr{C}_D^I+\mathscr{C}_M)\psi^{\xi}+(\mathscr{C}_T+\mathscr{C}_D^{II}+I_{\{2\le K\le M\}}(K)\mathscr{C}_{FB})(d_{sd}-\psi)^{\xi}\\
&+K\mathscr{C}_T\max(\psi^{\xi},(d_{sd}-\psi)^{\xi})\Big),
\end{aligned}
\tag{3.80}
$$

where

$$\mathscr{C}_T = -\frac{N_T}{\ln(1-\delta_{out})}, \;\; \mathscr{C}_D^I = KN_D, \;\; \mathscr{C}_M = \frac{M}{R},$$
$$\mathscr{C}_D^{II} = I_{\{K=1\}}(K)N_D\left(\sum_{j=1}^{M}\frac{1}{j}\right)^{-1} + I_{\{2\le K\le M\}}(K)\frac{N_D}{K}\left(1+\sum_{j=K+1}^{M}\frac{1}{j}\right)^{-1},$$

$$\mathscr{C}_{FB} = N_{FB}\left(\sum_{j=K}^{M}\frac{1}{j}\right)^{-1}.$$

In order to find $\psi_{opt}(K,M)$, two different cases have to be investigated.

Case I: $0 \le \psi \le \frac{d_{sd}}{2}$

Using the following substitutions in (3.80)

$$\alpha_I = \mathscr{C}_T + \mathscr{C}_D^I + \mathscr{C}_M,$$
$$\beta_I = (1+K)\mathscr{C}_T + \mathscr{C}_D^{II} + I_{\{2\le K\le M\}}(K)\mathscr{C}_{FB},$$

the optimization problem is given as follows

$$\begin{aligned}&\min_{\psi} \;\; \alpha_I\psi^{\xi} + \beta_I(d_{sd}-\psi)^{\xi}\\ &s.t.\\ &\psi \ge 0, \;\; \psi \le \frac{d_{sd}}{2}.\end{aligned} \tag{3.81}$$

It can be solved using KKT conditions [112]

$$\begin{aligned}\xi\left(\alpha_I\psi^{\xi-1} - \beta_I(d_{sd}-\psi)^{\xi-1}\right) + \lambda_1 - \lambda_2 &= 0,\\ \lambda_1\left(\psi - \frac{d_{sd}}{2}\right) &= 0,\\ \lambda_2\psi &= 0,\\ \lambda_1 \ge 0, \; \lambda_2 &\ge 0.\end{aligned}$$

The above conditions are only fulfilled for

$$\lambda_1 = \lambda_2 = 0,$$
$$\psi_I = \left(1 + \left(\frac{\alpha_I}{\beta_I}\right)^{\frac{1}{\xi-1}}\right)^{-1} d_{sd}. \tag{3.82}$$

Case II: $\frac{d_{sd}}{2} < \psi \leq d_{sd}$

Analogous to case I, it can be shown that

$$\psi_{II} = \left(1 + \left(\frac{\alpha_{II}}{\beta_{II}}\right)^{\frac{1}{\xi-1}}\right)^{-1} d_{sd}. \tag{3.83}$$

where

$$\alpha_{II} = (1+K)\mathscr{C}_T + \mathscr{C}_D^I + \mathscr{C}_M,$$
$$\beta_{II} = \mathscr{C}_T + \mathscr{C}_D^{II} + I_{\{2 \leq K \leq M\}}(K)\mathscr{C}_{FB},$$

As $\alpha_{II} > \alpha_I$ and $\beta_{II} < \beta_I$

$$\psi_{II} < \left(1 + \left(\frac{\alpha_I}{\beta_I}\right)^{\frac{1}{\xi-1}}\right)^{-1} d_{sd}, \tag{3.84}$$

i.e., $\psi_{II} < \psi_I$ and this violates $\psi_{II} > \frac{d_{sd}}{2}$. Therefore, the optimal solution is $\psi_{opt} = \psi_I$. $\square$

From (3.77) it can be seen that the optimal source-to-relay distance increases with d_{sd} and the path-loss exponent ξ. The accuracy of (3.77) will be evaluated through simulation in Section 3.5.

3.4 Overhead Analysis

The signalling overhead for the cooperative relaying system in Fig. 3.1 can be calculated as

$$\Omega_{pro} = (K+2)N_T + \frac{M+1}{R} + I_{\{2 \leq K \leq M\}}(K)N_{FB}. \tag{3.85}$$

It consists of three main parts. The first part is the overhead for training from the source to relays and from the destination to relays as well as the overhead for broadcasting training symbols from the K selected relays. The second part represents the overhead to signal the number of correctly decoding relays and to stop $M-K$ relay timers. The last part is the overhead needed to feedback the sum of K best channel power gains to the selected relays. Since the feedback from the destination is only required for cooperative beamforming ($K \geq 2$), the feedback overhead is multiplied by the indicator function $I_{\{2 \leq K \leq M\}}(K)$.

The signalling overhead for the cooperative relaying scheme in [20], which is referred to as the reference scheme hereafter, can be calculated as

$$\Omega_{ref} = MN_T + \Big(K_{ref} + I_{\{2 \leq K_{ref} \leq M\}}(K_{ref})\Big)N_{FB}, \tag{3.86}$$

where the number of selected relays, K_{ref}, is given by

$$K_{ref} = \begin{cases} 1, & M \leq 2 \\ 2, & 3 \leq M \leq 6 \\ 3, & 7 \leq M \leq 15 \end{cases} .$$

Compared to the reference scheme, the signalling overhead reduction achieved by the proposed scheme is given by

$$\begin{aligned} \Omega_{red} &= \left(\frac{\Omega_{ref} - \Omega_{pro}}{\Omega_{ref}}\right) 100\% \\ &= \left(\Big(M-K-2\Big)N_T + \Big(K_{ref} + I_{\{2 \leq K_{ref} \leq M\}}(K_{ref}) - I_{\{2 \leq K \leq M\}}(K)\Big)N_{FB} - \frac{M+1}{R}\right) \\ &\left(MN_T + \Big(K_{ref} + I_{\{2 \leq K_{ref} \leq M\}}(K_{ref})\Big)N_{FB}\right)^{-1} 100\%. \end{aligned} \tag{3.87}$$

When the number of correctly decoding relays approaches infinity, the overhead reduction converges to

$$\lim_{M \to \infty} \Omega_{red} = \left(1 - \frac{1}{RN_T}\right) 100\%, \tag{3.88}$$

which depends only on the data rate (R) and the number of training symbols (N_T) used for channel estimation. Increasing R and/or N_T for both schemes would lead to more significant overhead reduction by the proposed scheme.

3.5 Simulation Results

The performance of the proposed cooperative relaying scheme and the accuracy of the analytical results are evaluated through simulation. In the simulation, source and destination are located at $(0,0)$ and $(d_{sd},0)$, respectively. The $M(>1)$ relays that can correctly decode messages from the source, are situated close to one another with approximately the same distance ψ from the source. System parameters as listed in Table 5.1 conform to 3GPP LTE-A [113]. For illustration purposes we consider a single subcarrier with 16-QAM modulation, i.e., $R=4$. During training, one OFDM symbol ($N_T=1$) is transmitted at the target rate R with outage probability $\delta_{out}=0.12$. The destination utilizes two OFDM symbols ($N_{FB}=2$) to feedback the sum of second-hop channel power gains to the selected relays.

Table 3.1 System parameters

Carrier frequency, f_c	2.0 GHz
Reference distance, d_0	10 m
Path-loss exponent, ξ	4.0
Noise power spectral density, N_0	-174 dBm/Hz
Maximum transmission power, P_{max}	23 dBm
Subcarrier bandwidth, Δf	15 kHz
Symbol length, T_S	66.7 μs
Data packet length (in OFDM symbols), N_D	140
Source to destination distance, d_{sd}	500 m

Fig. 3.2 shows both the analytically calculated and simulated collision probability ($p_{coll,K,n_{max}}$) and relay selection time ($T_{sel,K}$) versus θ ($=\lambda/\Delta_g$) for two different numbers of selected relays and $M=10$. For a given Δ_g ($=N_T T_S$), λ controls the trade-off between $p_{coll,K,n_{max}}$ and $T_{sel,K}$. It can be seen that with increasing λ, the collision probability decreases, whereas the relay selection time increases. The results calculated using (3.6), (3.10), and (3.11) are in close agreement with those obtained from simulation. For a given θ, selecting one more relay leads to a higher collision probability and a higher relay selection time. In the following, we set $\theta=70$ as it provides a good trade-off between collision probability and relay selection time, both of which will be included in the evaluation of EE and spectral efficiency. With the parameter values in Table 5.1 and for $M=10$, it can be calculated using (3.6) and (3.18) that the minimum channel coherence time required for the proposed scheme is 22ms, which is significantly shorter than the channel coherence time $T_{coh}=76.1ms$ for low mobility scenario (with speed of 3km/h).

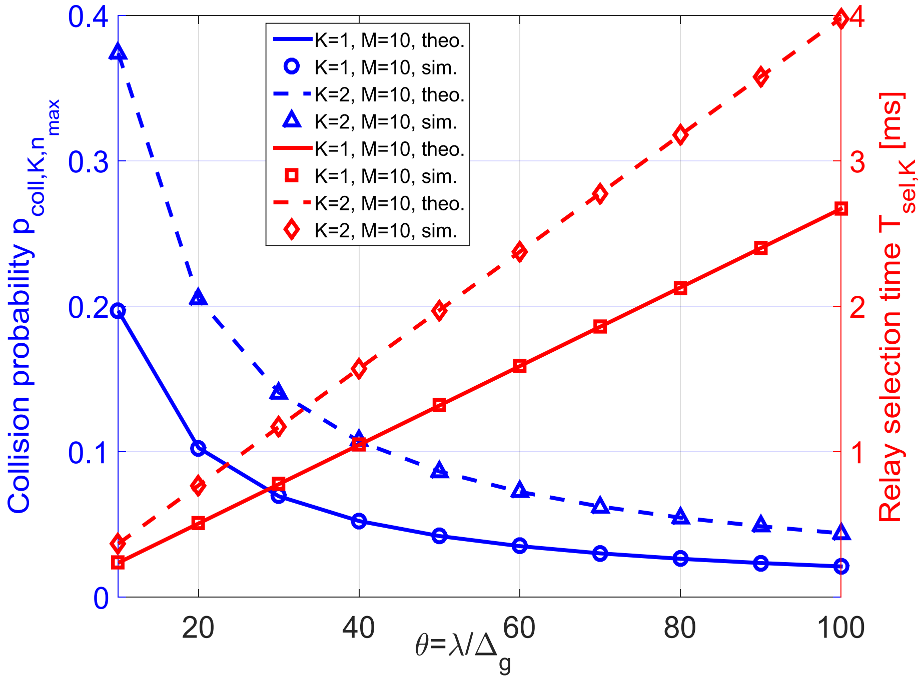


Fig. 3.2 Collision probability and relay selection time versus θ.

Fig. 3.3 plots the simulation results of average EE for $\psi = 50m$ over different values of M and K. It can be seen that the maximum average EE is achieved by selecting the $K = 2$ best relays. Furthermore, deploying all decoding relays, i.e., $K = M$ ($M > 2$), for cooperative beamforming exhibits the lowest EE, because the energy consumption for signalling overhead outweighs the energy savings from cooperative beamforming. For a given K, a larger number of correctly decoding relays (M) leads to a higher EE due to increased diversity gain.

Fig. 3.4 plots the optimal number of selected relays that maximizes the average EE obtained through simulations versus the source-to-relay distance. For $M = 3$ and $M = 5$ (the two curves overlap with each other), selecting the best two relays is optimal for source-to-relay distances up to 150m, beyond which the best relay selection ($K = 1$) maximizes the EE. This is because for long source-to-relay distances, the overhead energy consumption required to select one additional relay plus the extra source transmission power required to reach the additional relay in the first hop outweighs the energy savings from cooperative beamforming in the second hop. In the case of $M = 10$, the threshold source-to-relay distance reduces to 130m due to increased relay transmission collision probability. The results may change with different sizes of data packets (see Fig. 3.9 and Fig. 3.10).

In Fig. 3.5, the accuracy of the approximate optimal location of cooperative relays from (3.77) is evaluated by comparing it with simulation results. There is a good match between

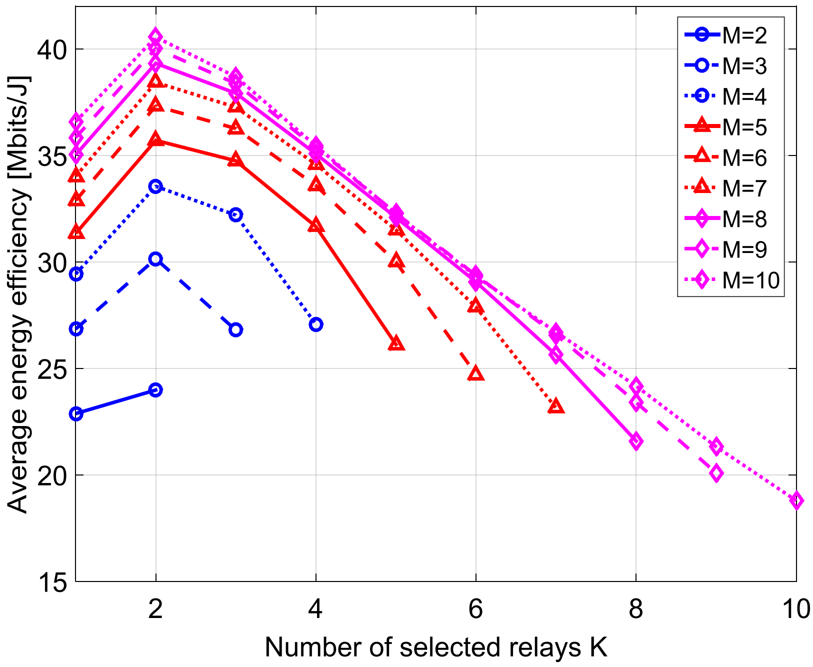


Fig. 3.3 Average energy efficiency versus the number of selected relays (K), for different numbers of correctly decoding relays (M) and $\psi = 50$m.

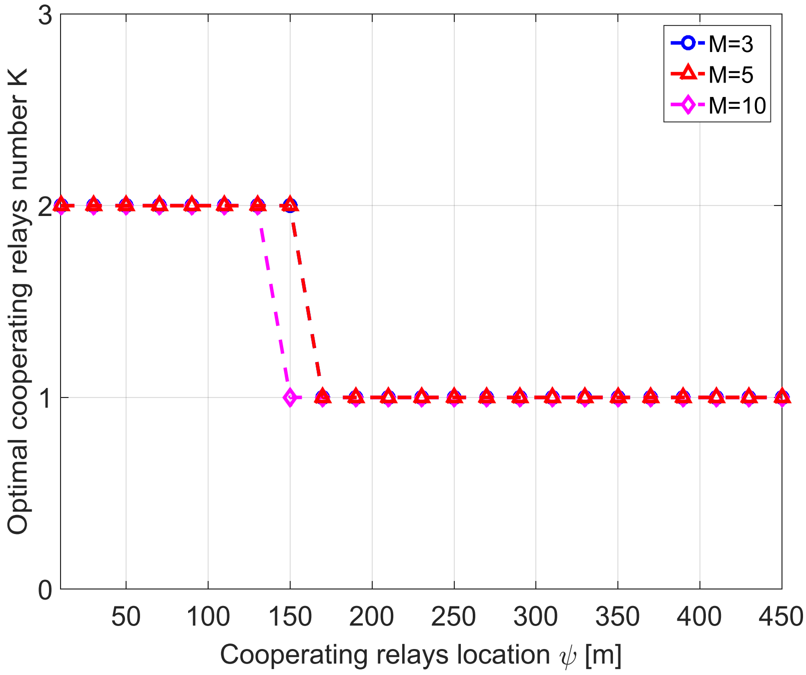


Fig. 3.4 Optimal number of cooperating relays versus their location for different values of M.

the theoretically calculated optimal location of relay(s) and that found through simulation for both the best relay selection and the proposed scheme. Conforming to the observation in Fig. 3.4, the optimal location of relays is closer to the source for the proposed scheme than for the best relay selection. For both schemes, as M increases (e.g., due to better first-hop channel conditions), the optimal location of relays gets only slightly closer to the source. This indicates that the optimal location of relay(s) can be predicted using (3.77) for both the proposed cooperative relaying scheme and the best relay selection, and the prediction does not need to be updated frequently.

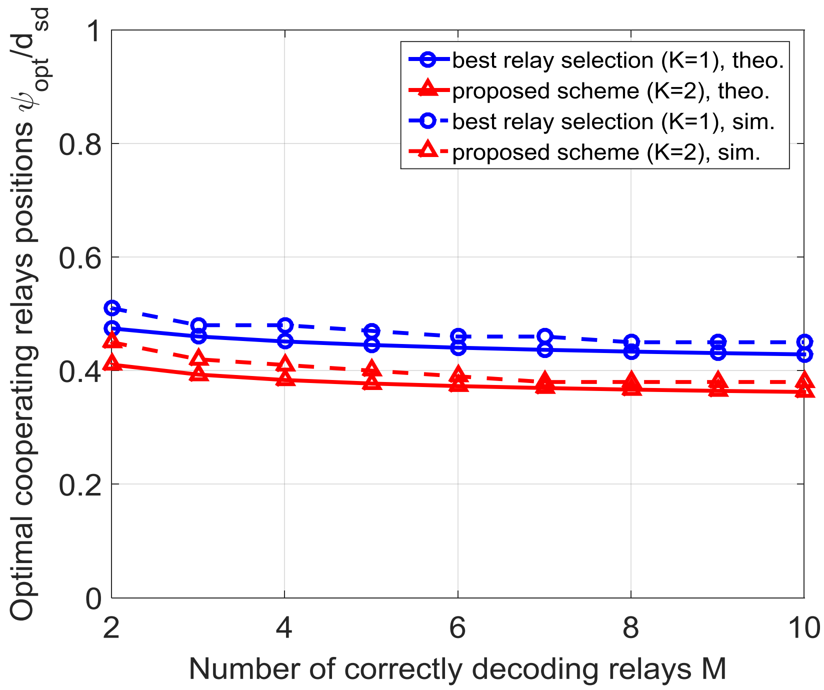


Fig. 3.5 Approximate optimal location of cooperative relays versus M.

In Fig. 3.6, the overhead reduction offered by the proposed scheme as compared to the reference scheme [20] calculated using (3.87) is depicted versus M for three different numbers of training symbols (N_T). The reduction in signalling overhead increases with increasing M for all considered N_T, due to the stronger dependence on M of the reference scheme than the proposed scheme, as shown in (3.86). For $M < 6$, a smaller N_T leads to a higher reduction in signalling overhead; while for $M > 8$, a larger N_T leads to a higher overhead reduction. As it can be seen from (3.87), for small M, e.g., $M = 3$, $M - K - 2 < 0$, and increasing N_T decreases the overhead reduction. According to (3.88) for large M, the signalling overhead reduction increases with N_T for given R. Significant increase of Ω_{red}

occurs from $M = 6$ to $M = 7$ because the reference scheme increases the number of selected relays from 2 to 3 as M increases from 6 to 7 (see (3.86)).

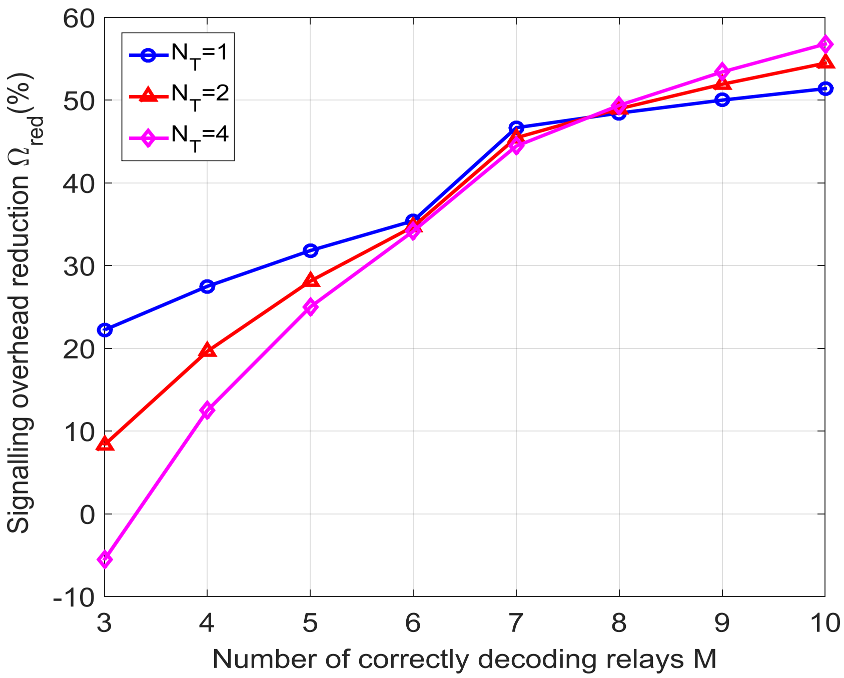


Fig. 3.6 Overhead reduction of the proposed cooperative relaying scheme over the reference scheme [20] for different numbers of training symbols N_T.

Table 3.2 shows signalling overhead reduction for the proposed scheme compared to the reference scheme [20] for different modulation orders and various numbers of training symbols. Conform to (3.88), increasing modulation order and/or number of training symbols leads to higher reduction in signalling overhead. For instance, increasing modulation order from 4-QAM to 64-QAM for $N_T = 1$, increases the overhead reduction from 36.11% to 56.48%.

Table 3.2 Signalling overhead reduction $\Omega_{red}(\%)$ compared to [20] for different modulation orders, $N_T = 1, 2$ and $M = 10$

Modulation order	4-QAM		16-QAM		64-QAM	
N_T	1	2	1	2	1	2
$\Omega_{red}(\%)$	36.11	44.64	51.39	54.46	56.48	57.73

In Fig. 3.7, the simulated average EE of the proposed scheme is compared to that of the reference scheme [20] for three different locations of cooperative relays. In [20], the source transmits data packets with a fixed transmission power. The M correctly decoding relays each transmit a training symbol to the destination, which performs channel estimation and selects the K_{ref} relays (as shown in Section 3.4) with the highest second-hop channel power gains. The destination feeds back first the corresponding channel power gain to each selected relay and then the sum of the K_{ref} channel power gains to all of them. The performance of the reference scheme with fixed source transmit power (P_{max}) is nearly independent of the relay location and the value of M. For a more comprehensive comparison, it is assumed that the source knows the minimum power required to reach all M correctly decoding relays, so that the reference scheme is also able to use adaptive source transmission power. The EE of the reference scheme is significantly improved due to the use of adaptive source transmission power. For $M > 2$, the proposed scheme offers higher EE than the reference scheme (with adaptive source transmit power) for all three cases, and the gap between the two schemes increases with M for each given relay location. This is mainly because of two reasons. First, the proposed scheme enables the source to adapt its transmission power to reach only the K selected relays ($K \leq M$), while the reference scheme requires a source transmission power that can reach all the M correctly decoding relays. Second, the energy consumption for signalling overhead is reduced in the proposed scheme. In contrary to the reference scheme that loses EE with increasing M for large values of M, the proposed scheme is able to maintain a stable EE at large values of M, indicating a much better scalability.

Comparison of average EE between the proposed cooperative relaying scheme, best relay selection, and direct transmission using adaptive transmission power is depicted in Fig. 3.8, where the position of cooperating relays is set at $\psi = d_{sd}/10$ for different d_{sd}. Fig. 3.8 presents both simulation results and theoretical results calculated using (3.60) and (3.75) for cooperative and direct transmissions, respectively. It can be seen that the theoretical results closely match the simulation results. Direct transmission is more energy efficient than the proposed scheme and best relay selection for $d_{sd} < 300m$, as it requires less signalling overhead. As d_{sd} increases, the EE of cooperative communications decreases much slower than direct transmission, leading to a higher EE for $d_{sd} \geq 300m$. This is because cooperative communications have lower outage probability and can use lower transmission power than direct transmission for long source-to-destination distances, due to the cooperative gains. The proposed scheme achieves higher EE than the best relay selection, because deploying one more relay offers higher cooperative gains.

Fig. 3.9 shows the simulation results of the average EE over different data packet sizes N_D for the proposed scheme and best relay selection. In all considered cases, increasing data packet size leads to higher EE, as data transmission becomes the dominant part in overall energy consumption and the impact of overhead diminishes. As shown in Fig. 3.3,

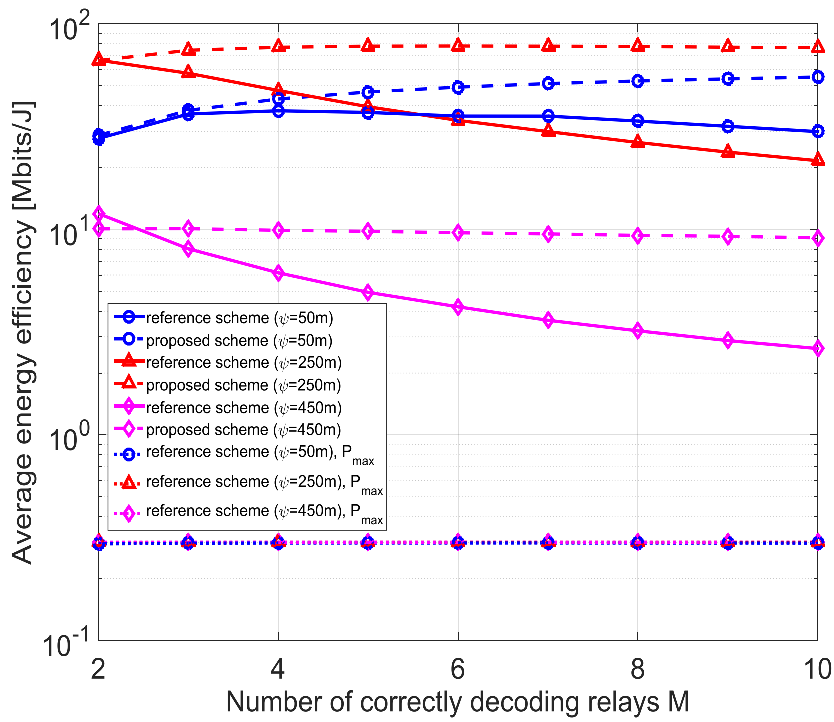


Fig. 3.7 Average energy efficiency for the proposed cooperative relaying scheme and the reference scheme [20] for three different locations of cooperating relays.

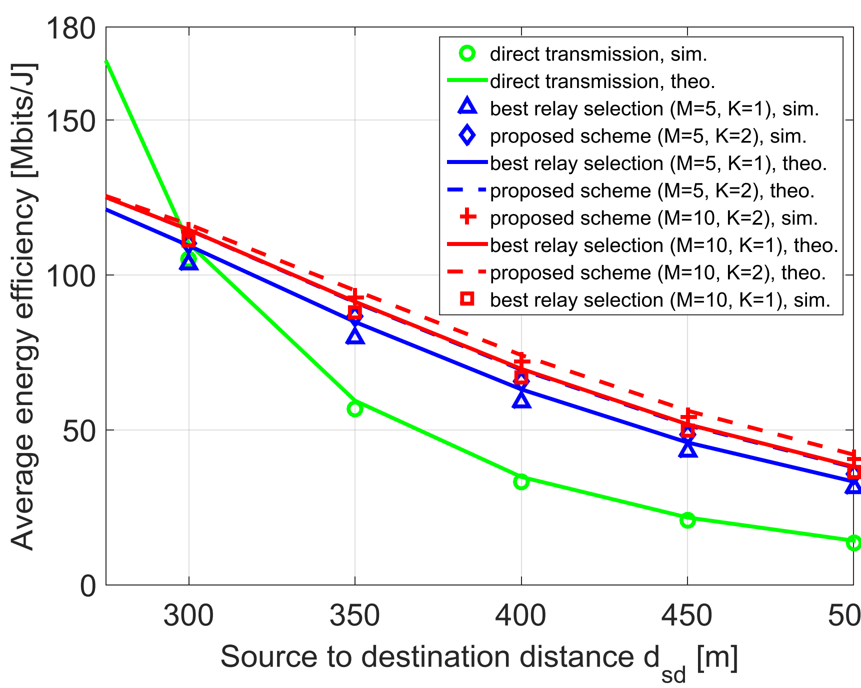


Fig. 3.8 Average energy efficiency comparison between direct transmission and cooperative communications for $\psi = d_{sd}/10$.

for $N_D = 140$ OFDM symbols, the optimal number of relays for cooperative beamforming is limited to $K = 2$ by the related signalling overhead. For $N_D > 200$ OFDM symbols, the optimal number of relays selected for cooperative beamforming increases to 3, because the impact of overhead on EE is mitigated by long data packets. The increase of K leads to a higher cooperative beamforming gain, which further improves the EE.

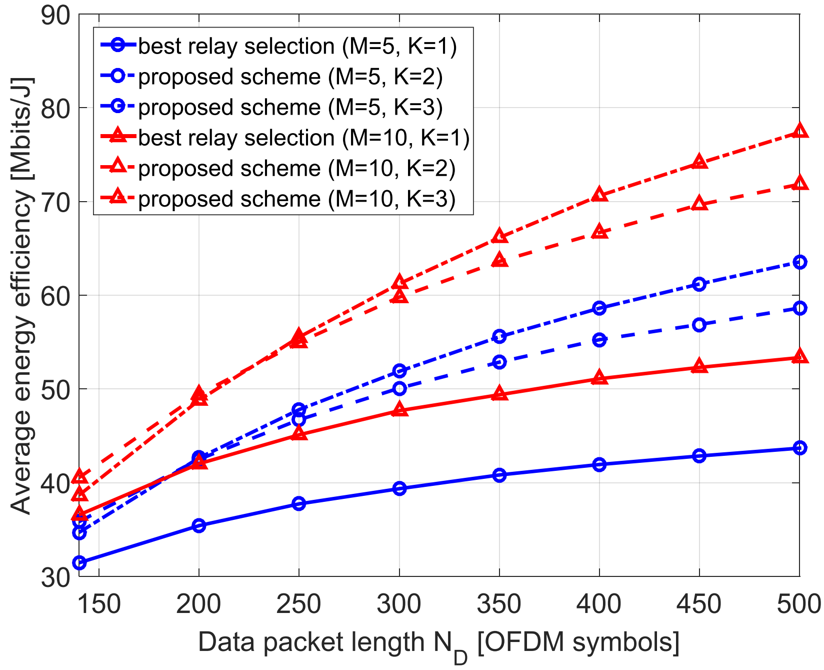


Fig. 3.9 Average energy efficiency versus data packet length for different M and K, and $\psi = 50m$.

Fig. 3.10 plots the optimal number of selected relays (K) that maximizes the average EE obtained through simulation versus data packet size (N_D) for three different values of M. Due to the same reason as explained for Fig. 3.9, the optimal number of cooperating relays increases with the data packet length for each given M. Moreover, for a large data packet size (e.g., $N_D > 200$ OFDM symbols), K also increases with M, because increasing M offers a higher diversity gain, thus allowing the recruiting of more relays.

In the following, a comparison of spectral efficiency (SE) is included to make the performance evaluation more comprehensive. The SE of direct transmission is given by [18]

$$SE_{DT} = (1 - p_{out}^{DT}) \frac{R}{B} \left(\frac{T_{coh} - T_O^{DT}}{T_{coh}} \right), \tag{3.89}$$

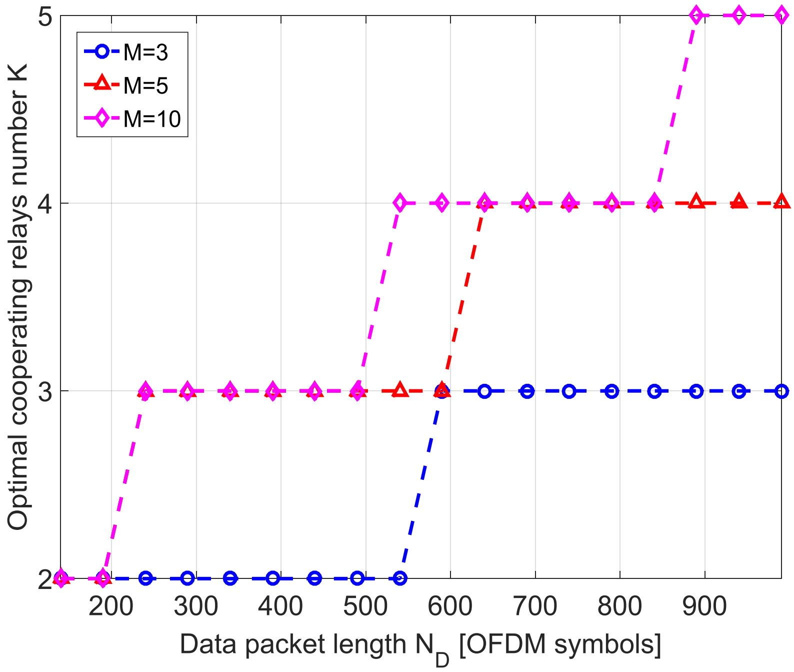


Fig. 3.10 Optimal number of cooperating relays versus data packet size for different values of M and $\psi = 50m$.

where p_{out}^{DT} and T_{coh} are the outage probability of direct transmission and channel coherence time, respectively, and $T_O^{DT} = (N_T + N_{FB})\,T_S$ denotes the overhead transmission time (i.e., source training and destination feedback for CSI) of direct transmission. With the half-duplex DF relays, which cannot receive and transmit simultaneously in the same band, the SE of the proposed cooperative relaying scheme can be calculated as

$$SE_{CC} = \frac{1}{2}(1 - p_{out}^{CC})(1 - p_{coll,K,n_{max}})\frac{R}{B}\left(\frac{T_{coh} - T_{sel,K} - T_O^{CC}}{T_{coh}}\right), \tag{3.90}$$

where the factor 1/2 results from the two-hop half-duplex transmission, p_{out}^{CC} is given in (3.20), and $T_O^{CC} = \left((K+2)N_T + N_{FB} + \frac{M+1}{R}\right) T_S$ is the overhead transmission time of cooperative relaying.

Fig. 3.11 shows the SE of the proposed scheme, the best relay selection, and the reference scheme [20] normalized with respect to that of direct transmission (i.e, SE_{CC}/SE_{DT}) versus d_{sd} for $M = 10$ and two different modulation orders. The normalized SE of the best relay selection and the proposed scheme in the ideal case without any relay transmission collision or delay due to relay selection (i.e., $p_{coll,K,n_{max}} = 0$, $T_{sel,K} = 0$) is also plotted. In the ideal

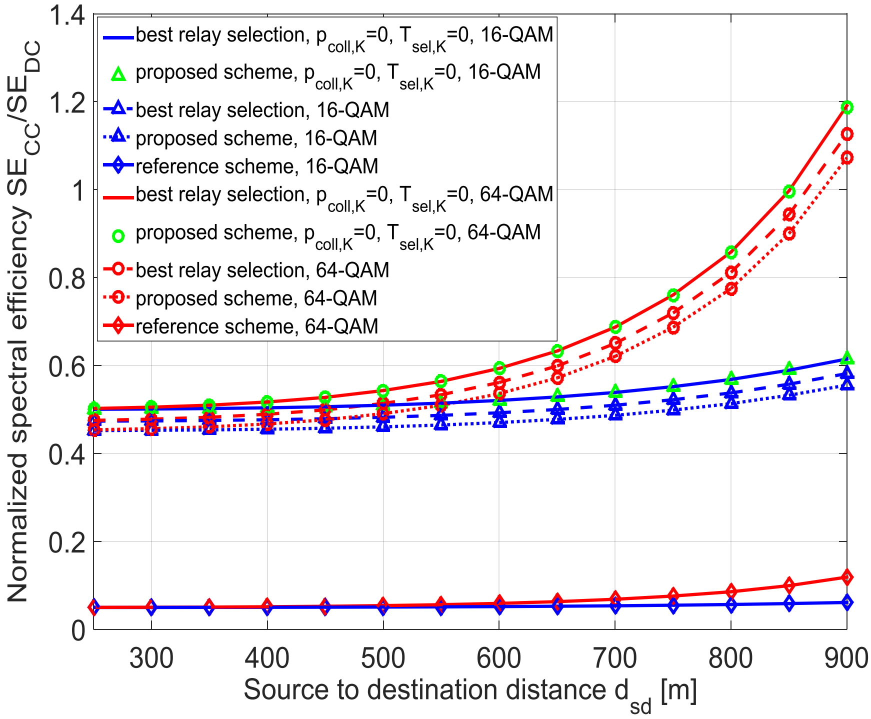


Fig. 3.11 Normalized spectral efficiency comparison between best relay selection, the proposed scheme and the reference scheme for $M = 10$, 16-QAM and 64-QAM.

case, the proposed scheme and the best relay selection achieve the same SE. It can be seen that with relay transmission collisions and relay selection time taken into account, the SE of the proposed scheme is reasonably close to that of the ideal case. This shows that the loss of SE caused by the proactive relay subset selection in the proposed scheme is reasonably low. In most cases considered in Fig. 3.11, the normalized SE is less than one, i.e., cooperative communications are less spectral efficient than direct transmission. This is mainly due to the factor 1/2 in (3.90) of half-duplex relaying. For each considered modulation, the normalized SE of the proposed scheme and the best relay selection is much higher and increases much faster with d_{sd} than that of the reference scheme. This indicates that while the SE of direct transmission decreases with d_{sd}, the proposed scheme and the best relay selection achieve much higher SE than the reference scheme at long source-to-destination distances. The reason is that the reference scheme requires the relays to transmit on orthogonal subcarriers in order to ensure the orthogonality between relay transmissions during the training phase [20], while in the proposed scheme relays contend with each other for the same subcarrier. For 64-QAM and $d_{sd} > 860m$, the proposed scheme is more spectral efficient than direct transmission. The proposed scheme exhibits slightly lower SE than the best relay selection owing to the higher collision probability and longer relay selection time for deploying more relays.

3.6 Summary

In this chapter, an energy-efficient and low signalling overhead cooperative relaying scheme is proposed that selects a subset of DF relays for cooperative beamforming in a proactive manner by relays using their local timers. Theoretical analysis of EE under maximum transmission power constraint, with practical data packet length, and considering the overhead for obtaining CSI, relay selection, and cooperative beamforming is carried out. The accuracy of derived expression of average EE and closed-form approximate expression for the optimal location of relays that maximizes EE has been verified by simulation results. The analytical and simulation results have shown that the proposed scheme not only reduces the signalling overhead significantly, but also exhibits higher EE compared to the existing energy-efficient cooperative relaying scheme [20], best relay selection, all relay selection, and direct transmission, especially for relays located close to the source. It is also demonstrated that EE of cooperative relaying increases with data packet size under the constraint of channel coherence time. The obtained results can be used as a guideline for developing dynamic energy-efficient cooperative transmission strategies that can adapt to different channel and system conditions.

Chapter 4

Energy Efficiency of Location-Aware Clustered Cooperative Beamforming without Destination Feedback

The conventional cooperative beamforming schemes require channel state information (CSI) exchanges among nodes, which increase energy consumption and are susceptible to quantization errors in practical systems.

In this Chapter, an energy-efficient and location-aware clustered cooperative beamforming scheme with low-overhead timer based relay selection is proposed. In the proposed scheme, relays know the locations and can overhear transmissions of each other. Utilizing the location awareness, the timers set at the relays and their overhearing capabilities, the proposed scheme requires no CSI feedback from the destination to calculate optimal beamforming weights.

The Chapter is organised as follows. In Section 4.1 the system model of the proposed cooperative communication scheme is described. Section 4.2 analyses the associated energy efficiency (EE). Simulation results are presented in Section 4.3. In Section 4.4 summary is given.

4.1 System Model

One source-destination pair and N decode-and-forward (DF) relays are considered. The channel power gains from the source to relay R_i and from relay R_i to the destination are denoted by h_i and g_i ($i = 1, \ldots, N$), respectively, which follow independent exponential distributions with the corresponding means $\overline{h}_i = (\lambda_c/4\pi d_0)^2 (d_{si}/d_0)^{-\xi}$ and $\overline{g}_i = (\lambda_c/4\pi d_0)^2 (d_{id}/d_0)^{-\xi}$.

Thereby, λ_c is the carrier wavelength, d_0 is the reference distance, d_{si} and d_{id} are the distances from source to relay R_i and from relay R_i to the destination, respectively, and ξ is the path-loss exponent. It is assumed that the clustered relays are relatively close to one another leading to approximately same distances to the source and destination, i.e., $\overline{h}_i = \overline{h}$ and $\overline{g}_i = \overline{g}$ $(i = 1,\ldots,N)$, and the relays within the cluster can overhear each other's transmissions and know their own and each other's locations [38]. Furthermore, reciprocal channels are considered that remain the same during training, relay selection and transmission of a data packet. Each node deploys a single antenna, and is subject to additive white Gaussian noise (AWGN) with spectral density of N_0. Perfect channel estimation at each node is assumed. The communication between each pair of nodes is performed with fixed rate R (bits/symbol) and bandwidth B (Hz).

An energy-efficient and overhead-aware cooperative relaying scheme is proposed that consists of three main phases: relay channel estimation, relay selection and data transmission.

4.1.1 Relay Channel Estimation Phase

Training symbols are transmitted from the source and the destination to enable the relays to estimate the corresponding channels. The training transmission powers for the first hop P_T^S and the second hop P_T^D are chosen such that they support rate R with outage probability δ_{out}, i.e.,

$$P_T^S = N_0 B \frac{1-2^R}{\overline{h}\ln(1-\delta_{out})}, \tag{4.1}$$

$$P_T^D = N_0 B \frac{1-2^R}{\overline{g}\ln(1-\delta_{out})}, \tag{4.2}$$

where $\overline{h}$ and $\overline{g}$ are the corresponding mean channel power gains.

4.1.2 Relay Selection Phase

Relays R_j $(j = 1,\ldots,N)$ with the signal-to-noise ratio (SNR) γ_{sj} of the signal received from the source no less than the threshold $\gamma_{th} = 2^R - 1$ form a relay cluster

$$\mathscr{R} = \{R_{1\leq j\leq N} : \gamma_{sj} \geq \gamma_{th}\}$$

, where γ_{th} is calculated from Shannon's capacity formula. As it will be shown in Section 4.3, the source has to obtain the relay cluster size $M = |\mathscr{R}|$, in order to select the optimal number of relays K that maximizes EE of the cooperative relaying system. Hereafter, the M relays R_j ($j = 1, \dots, M$) in the set $\mathscr{R}$ are numbered in descending order of their second-hop channel power gains, i.e., $g_{1:M} > \dots > g_{j:M} > \dots > g_{M:M}$. To help the source obtain the value of M, each relay in set $\mathscr{R}$ sends one bit "1" to the source. The overall transmit power used by the M relays to signal cluster size M to the source is given by

$$P_M = \sum_{j=1}^{M} P_M^j = N_0 B(2^R - 1) \sum_{j=1}^{M} \frac{1}{h_j}. \tag{4.3}$$

At the same time, each relay $R_j \in \mathscr{R}$, starts a timer as follows

$$t_{j:M} = \lambda / g_{j:M}, \quad g_{1:M} > g_{2:M} > \dots > g_{M:M}, \tag{4.4}$$

where λ is a constant parameter in unit of time [35]. Accordingly, the timer of the relay with the strongest second-hop channel power gain expires first, followed by the second strongest relay to destination link and so on.

Relay R_j broadcasts training symbols and its relay index (RI) with the transmit power $P_T^R = P_T^S$ when its timer t_j expires. In order to avoid collisions between relay transmissions, relay R_j inserts a guard interval of $(j-1)\Delta_g$ in addition to its timer duration $t_{j:M}$ as depicted in Fig. 4.1, where Δ_g is given by

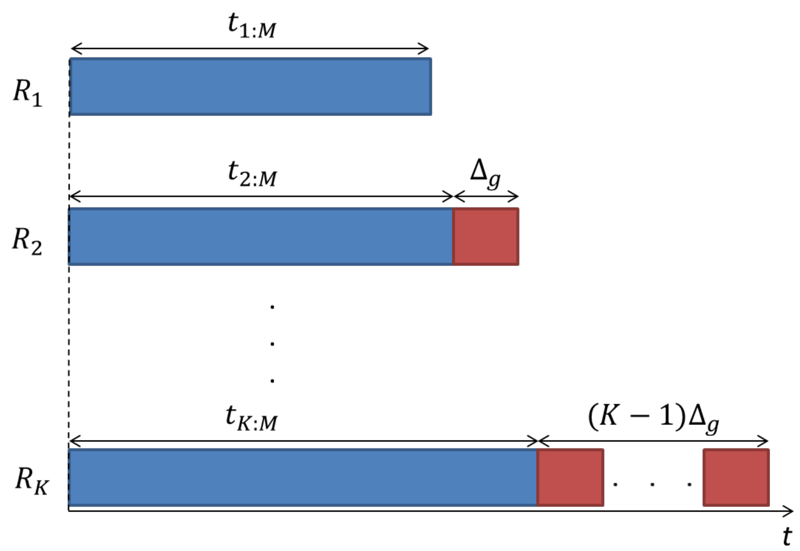


Fig. 4.1 Proposed guard interval insertion mechanism for the K selected relays.

$$\Delta_g = N_T + N_{RI} = N_T + \frac{\lceil \log_2(N) \rceil}{R}, \quad N \geq 2, \tag{4.5}$$

where N_T and N_{RI} are the numbers of symbols used for training and to signal RI, respectively. Although the relays R_j ($j = 1, \ldots, M$) in set $\mathscr{R}$ do not know their ranking in the set, the guard interval insertion shown in Fig. 4.1 can be achieved by each relay that still has an unexpired timer inserting an interval of Δ_g in addition to its timer duration every time it overhears the transmission from another relay. More specifically, relay R_1 does not need to insert any guard interval because its timer expires first and it transmits first; relays $R_2, \ldots, R_M$ each insert a time interval of Δ_g once they overhear the transmission of relay R_1; relays $R_3, \ldots, R_M$ each insert an additional time interval of Δ_g when they overhear the transmission from relay R_2. This continues until the first K timers (belonging to the K selected relays) have expired. The value of K is determined through simulations as it will be shown in Section 4.4. The residual collision probability due to propagation delays between the relays, which have not been considered in the above guard interval insertion scheme, is negligible as the clustered relays are close to each other.

Let x_i and x_j be the locations of relays R_i and R_j, respectively. Using the timing diagram shown in Fig. 4.2, relays R_i and R_j can obtain each other's second hop channel power gains without CSI feedback from the destination as follows

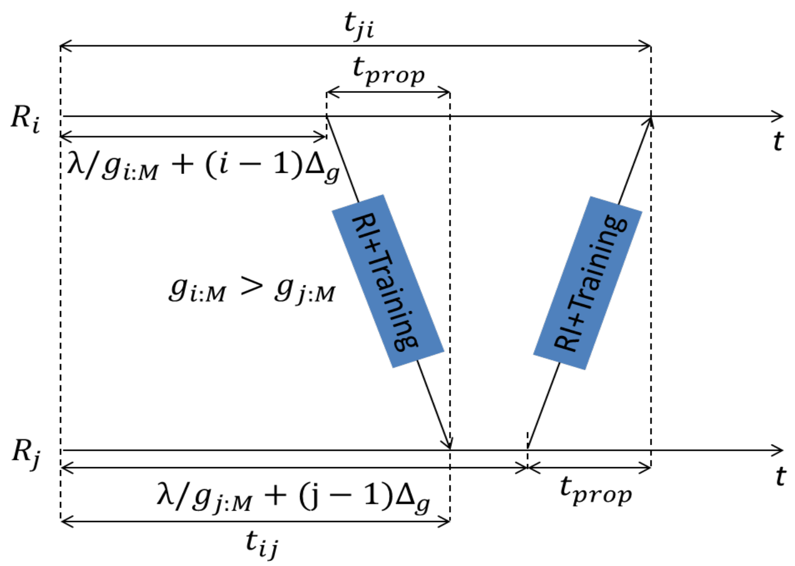


Fig. 4.2 Timing diagram for relays R_i and R_j for exchange of RI and training symbols, where $i < j$.

$$g_{i:M} = \frac{\lambda}{t_{ij} - (i-1)\Delta_g - t_{prop}}, \tag{4.6}$$

$$g_{j:M} = \frac{\lambda}{t_{ji} - (j-1)\Delta_g - t_{prop}}, \tag{4.7}$$

where t_{ij} (t_{ji}) is the time duration from the point in time when relay R_j (R_i) starts its timer until it overhears the transmissions from relay R_i (R_j), $t_{prop} = \left\|x_i - x_j\right\|_2 / c$ is the propagation delay between R_i and R_j, and c is the speed of light.

As soon as the source gets the training symbols of the first K relays, it requests the remaining $M-K$ relays to invalidate their timers and not to transmit any training symbols by broadcasting a single bit "0" with the maximum transmit power P_{max}.

Different from the Chapter 3, CSI feedback from the destination is dispensable. Consequently K selected relays are not required to transmit N_T training symbols to the destination. In this way, the energy consumption for the overhead can be reduced and as it will be shown in Section 4.3 more relays can be recruited for cooperative beamforming leading to higher beamforming gains.

4.1.3 Data Transmission Phase

The source estimates the first-hop CSI of the K selected relays based on the training symbols received from them, and then transmits data packets with the adaptive transmission power given by

$$P_{AD} = \frac{N_0 B(2^R - 1)}{\min\{h_1, \ldots, h_K\}}. \tag{4.8}$$

In the second hop, the selected K relays forward the received data packet from the source to the destination using cooperative beamforming. The overall transmission power for this case is given by

$$P_{CB} = N_0 B(2^R - 1) \sum_{i=1}^{K} \left(\frac{1}{\sqrt{g_{i:M}}} \sum_{j=1}^{K} g_{j:M} \right)^{-2}. \tag{4.9}$$

4.2 Analysis of Energy Efficiency

Without loss of generality, the relay cluster size $M \geq 2$ is assumed. The instantaneous EE can be calculated as

$$EE_{CC}(K,M,\psi) = \begin{cases} \frac{RN_D}{E_O(K,M,\psi)+E_D(K,M,\psi)}, \; g_{K:M} \geq \mu = N_0B(2^R-1)/P_{max} \\ 0, \; otherwise \end{cases}, \tag{4.10}$$

where ψ and N_D are the relay cluster location and the data packet length, respectively. $E_O(.)$ is the energy consumed for signalling overhead and $E_D(.)$ denotes the energy consumed for data transmission. Since $M \geq 2$, outage can occur only in the second hop if $g_{K:M} < \mu$. For this case instantaneous EE is zero.

$E_O(.)$ incorporates the energy consumed for training ($E_T(.)$), for relay signalling M to the source ($E_M(.)$) and for the source requesting non-selected relays to invalidate their timers (E_{INV}), i.e.,

$$E_O(K,M,\psi) = E_T(K,M,\psi) + E_M(M,\psi) + E_{INV}, \tag{4.11}$$

where

$$E_T(K,M,\psi) = N_0BT_S\left(\frac{1-2^R}{\ln(1-\delta_{out})}\right)\left(\frac{K(N_T+N_{RI})+N_T}{\overline{h}} + \frac{N_T}{\overline{g}}\right), \tag{4.12}$$

$$E_M(M,\psi) = N_MT_SN_0B(2^R-1)\sum_{i=1}^{M}\frac{1}{h_i}, \tag{4.13}$$

$$E_{INV} = N_{INV}T_SP_{max}, \tag{4.14}$$

in which N_M and N_{INV} are the numbers of symbols used for signalling M to source and for invalidating relay timers, respectively. T_S denotes symbol duration.

The energy consumption for data transmission $E_D(.)$ consists of two parts: energy consumed in the first hop $E_D^I(.)$ and that in the second hop $E_D^{II}(.)$, i.e.,

$$E_D(K,M,\psi) = E_D^I(K,M,\psi) + \begin{cases} E_D^{II}(K=1,M,\psi), \; K=1 \\ E_D^{II}(K>1,M,\psi), \; K>1 \end{cases}. \tag{4.15}$$

The energy consumed in the first hop is given by

$$E_D^I(K,M,\psi) = N_D T_S N_0 B \left(\frac{2^R - 1}{\min(h_1,\ldots,h_K)} \right). \tag{4.16}$$

The energy consumptions during the second hop data transmission for $K = 1$ and $K > 1$ are given by

$$E_D^{II}(K=1,M,\psi) = N_D T_S N_0 B \left(\frac{2^R - 1}{g_{1:M}} \right), \tag{4.17}$$

$$E_D^{II}(K>1,M,\psi) = N_D T_S N_0 B (2^R - 1) \sum_{i=1}^{K} \left(\frac{1}{\sqrt{g_{i:M}}} \sum_{j=1}^{K} g_{j:M} \right)^{-2}. \tag{4.18}$$

4.3 Simulation Results

The performance of the proposed cooperative relaying scheme in terms of average EE is evaluated through simulations. Average EE is obtained by averaging of instantaneous EE from (4.10) over 10^5 different channel realizations. In the simulations, the source and the destination are placed at the origin (0,0) and at (d_{sd},0), respectively. The values of simulation parameters are set according to 3GPP LTE-A [113], and are listed in Table 5.1. A single subcarrier and 16-QAM modulation ($R = 4$ bits/symbol) are considered. $N_T = 1$ OFDM symbol is used for training with transmission power P_T to satisfy the target rate R with the outage probability $\delta_{out} = 0.1$.

Table 4.1 Simulation parameters

Carrier frequency, f_c	2.0 GHz
Reference distance, d_0	10 m
Path-loss exponent, ξ	4.0
Noise power spectral density, N_0	-174 dBm/Hz
Maximum transmission power, P_{max}	23 dBm
Subcarrier bandwidth, Δf	15 kHz
Symbol length, T_S	66.7 μs
Data packet length (in OFDM symbols), N_D	140
Source to destination distance, d_{sd}	500 m

Fig. 4.3 depicts the average EE over different numbers of selected relays (K) for relay cluster located relatively close to the source ($\psi = 50m$). Average EE increases with increasing number of selected relays (K) because of the cooperative beamforming gains and the resulting

energy savings. We can see that for $M \leq 3$, $K = M$ maximizes the EE. While for $3 < M \leq 9$, $K = M - 1$ and for $M = 10$, $K = 8$ maximize the EE. For $M > 3$, recruiting all available relays for cooperative beamforming (i.e, $K = M$) does not lead to the highest EE, due to the additional overhead energy consumption and high outage probability caused by the $M - K$ relays that will not be selected by our proposed scheme. The average EE also increases with M for a given K, mainly due to the higher diversity gain offered by a larger M.

The impact of relay cluster location on the average EE for different relay selection schemes is depicted in Fig. 4.4. The proposed cooperative relaying scheme outperforms both the best relay selection and all relay selection schemes for relay cluster locations relatively close to the source. This is because the proposed scheme selects the optimal number of relays for a given M according to Fig. 4.3.

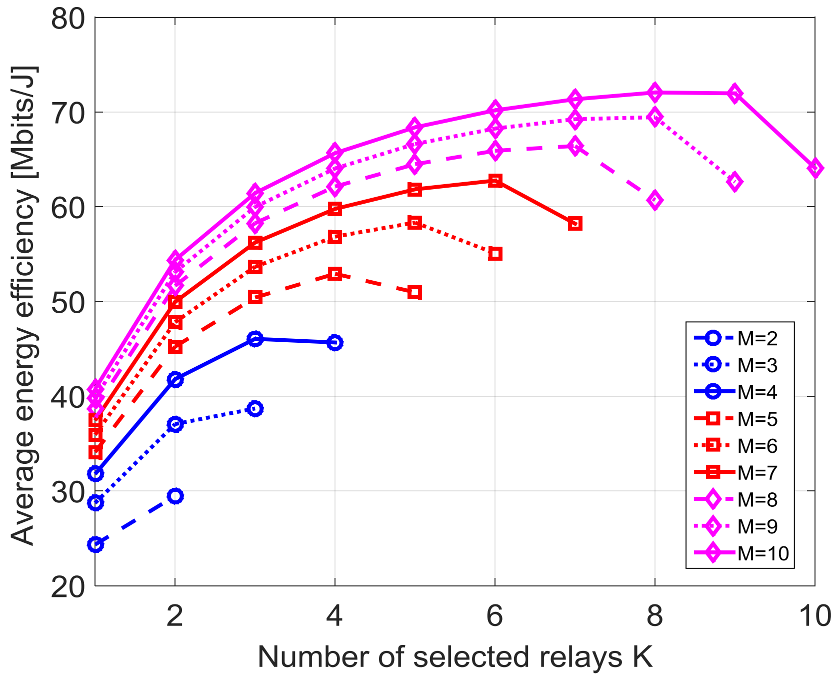


Fig. 4.3 Average energy efficiency over different number of selected relays K and various values of M.

Fig. 4.5 shows that in addition to M, the number of selected relays depends also on the relay cluster location. For all the considered values of relay cluster size M, the optimal number of selected relays K decreases when the relay cluster locates further away from the source. This is due to the fact that with increasing source-to-relay distance, the energy consumption in the first hop starts to dominate the overall energy consumption. Therefore, the

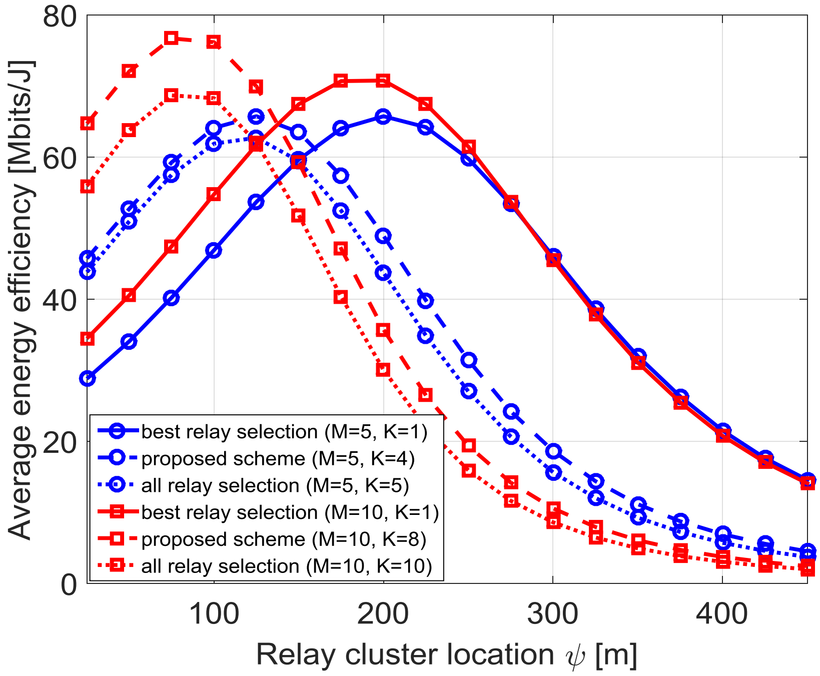


Fig. 4.4 Average energy efficiency over relay cluster location for different relay selection schemes.

additional energy consumed in the first hop by recruiting more relays cannot be compensated with energy savings in the second hop through cooperative beamforming.

In Fig. 4.6, the average EE of the proposed scheme is compared to the cooperative relaying scheme in [20] for three different relay cluster locations: close to the source ($\psi = 50$m), in the middle ($\psi = 250$m) and close to the destination ($\psi = 450$m). It can be observed from Fig. 4.6 that the average EE of the proposed scheme decreases with the increasing distance of the relay cluster from the source, while the average EE of the scheme in [20] is independent of the relay cluster location and the value of M. This is because the proposed scheme uses adaptive source transmission power that increases with higher source-to-relay distances, while the reference scheme of [20] uses maximum source transmission power and is less sensitive to relay cluster position. For all different locations of relay cluster and different values of M considered, the proposed scheme outperforms the cooperative relaying scheme in [20]. In addition to using adaptive source transmission power and reducing energy consumption for overhead, the proposed scheme removes the requirement of destination feeding back second-hop CSI for cooperative beamforming and can thus employ more relays for cooperative beamforming as compared to [20], leading to higher cooperative beamforming gains that further increase EE.

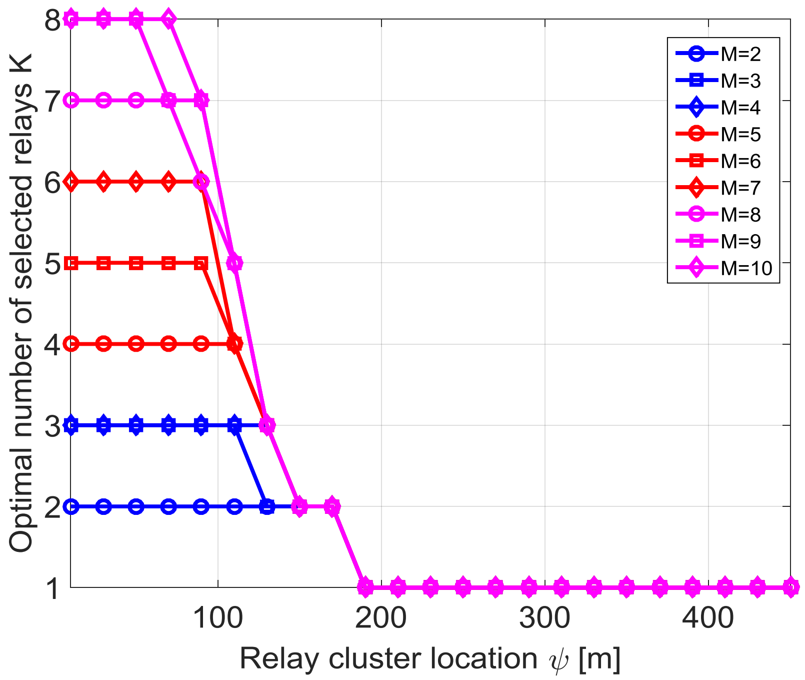


Fig. 4.5 The optimal number of selected relays over their locations and different values of M.

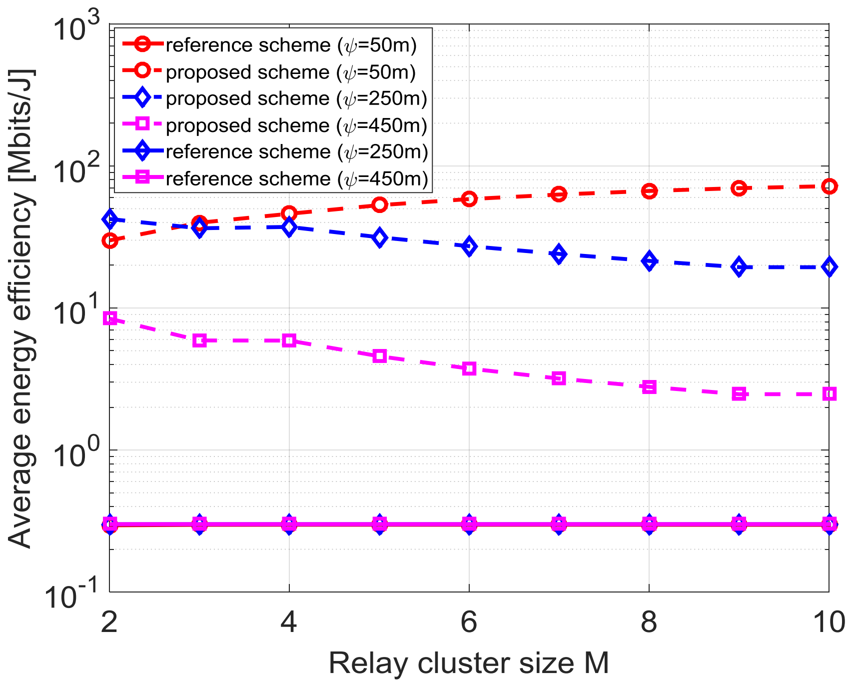


Fig. 4.6 Average energy efficiency comparison between the proposed cooperative relaying scheme and the reference scheme [20] for three different cluster locations.

Fig. 4.7 compares the average EE of the direct communication, best relay selection and the proposed scheme for different distances from source to destination (d_{sd}). For the direct communication the destination uses $N_{FB} = 2$ OFDM symbols to feeback estimated CSI to the source. The direct communication needs much less overhead as compared to the cooperative communications. Therefore, it is more energy efficient for relative short source-to-destination distances ($d_{sd} \leq 275$m), over which a reliable direct communication link can be set up. As d_{sd} increases, the average EE of the proposed scheme decreases much slower than that of the direct communication. For $d_{sd} > 275$m, the proposed scheme outperforms the direct communication. At relatively long source-to-destination distances, the proposed scheme achieves the highest EE among the three considered scheme, because the diversity and beamforming gains of the proposed scheme enables it to use lower transmission power and achieve lower outage probability than the direct communication and the best relay selection scheme.

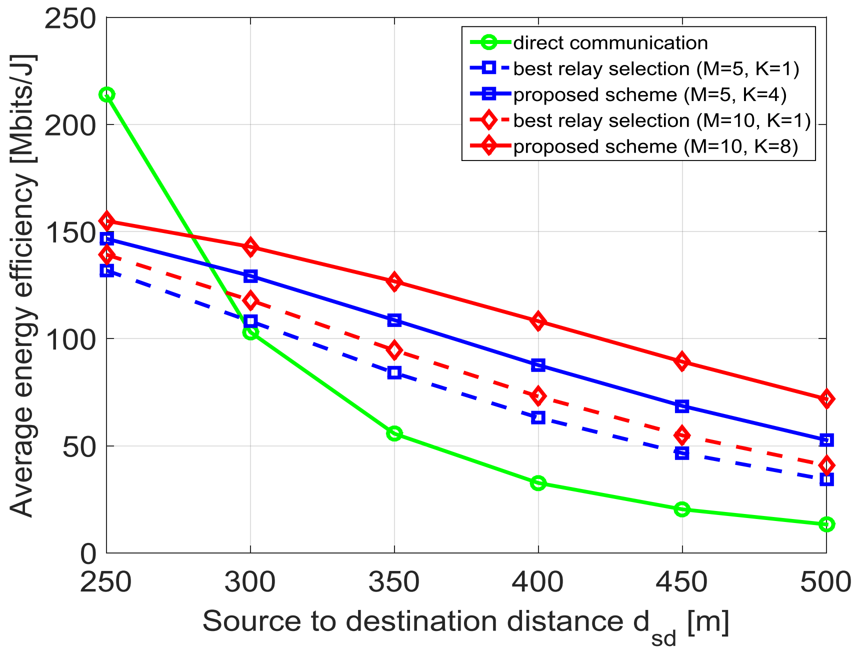


Fig. 4.7 Average energy efficiency over different source-to-destination distances d_{sd} for direct communication, best relay selection and the proposed scheme. Relay cluster location is set to $\psi = d_{sd}/10$.

4.4 Summary

In this chapter, a new cooperative relaying scheme is proposed that combines low-overhead timer-based relay selection, location-awareness, and energy-efficient cooperative beamforming without requiring CSI feedback from the destination. In order to avoid collisions between relay transmissions, a mechanism is introduced, where the selected relays insert appropriate guard intervals before their transmissions. The system EE with maximum transmission power constraint and considering the overhead to perform channel estimation, relay selection and cooperative beamforming is analysed. The number of relays and cluster location that maximize the EE have been identified. It is shown that the proposed cooperative relaying scheme using the optimal number of selected relays outperforms the reference scheme [20], the best relay selection, all relay selection and direct communication.

Chapter 5

Energy-and Spectral-Efficient Adaptive Forwarding Strategy for Two-Hop Device-to-Device Communications Overlaying Cellular Networks

Device-to-device (D2D) communications facilitate user equipments (UEs) to communicate directly to each other utilizing cellular resources. It is considered as a key technique to enhance energy efficiency (EE) and spectral efficiency (SE) of cellular networks. In reality, the channel conditions between the source UE (SUE) and the destination UE (DUE) may not be favourable for direct transmissions. In this case, two-hop D2D communications can be deployed, where relay UEs (RUEs) forward data of the SUE to the DUE.

In this Chapter, an energy- and spectral-efficient optimal adaptive forwarding strategy (OAFS) for two-hop D2D communications is proposed where RUEs adaptively and in distributed manner choose between best relay forwarding (BRF) and cooperative relay beamforming (CRB) with optimal number of RUEs. In addition, a sub-optimal adaptive forwarding strategy (SAFS) that switches between BRF and CRB with two RUEs is proposed to lower the computational complexity. The average EE and SE of OAFS and SAFS are investigated considering maximum transmission power constraint, circuit power consumption and the overhead for acquisition of channel state information (CSI), forwarding mode selection, and cooperative beamforming.

The Chapter is organized as follows. The system model is presented in Section 5.1. The proposed optimal and sub-optimal adaptive forwarding strategies for two-hop D2D communications are described in Section 5.2. Section 5.3 analyses the average EE and

SE for two-hop D2D communications utilizing the proposed forwarding strategies, direct D2D communications, and cellular communications. The simulation results are presented in Section 5.4. Finally, the paper is summarized in Section 5.5.

5.1 System Model

A D2D communications overlaying a cellular network is considered as depicted in Fig. 5.1. The SUE intends to transmit data packets to the DUE. The data transmission from SUE to DUE can be realized in three different ways: conventional cellular communications via the BS, direct D2D communications between SUE and DUE, and two-hop D2D communications through half-duplex decode-and-forward (DF) RUEs. The channel power gains between any two nodes are exponentially distributed and are represented as follows: h_B is the channel power gain between SUE and BS; h_0 is the channel power gain between SUE and DUE; h_i (i=1,...,N) denotes the channel power gain from SUE to RUE_i; g_B is the channel power gain between BS and DUE; and g_i (i=1,...,N) denotes the channel power gain from RUE_i to DUE. It is assumed that only $RUE_{1\leq i\leq|\mathscr{D}|}$ can correctly decode the received data from SUE and are

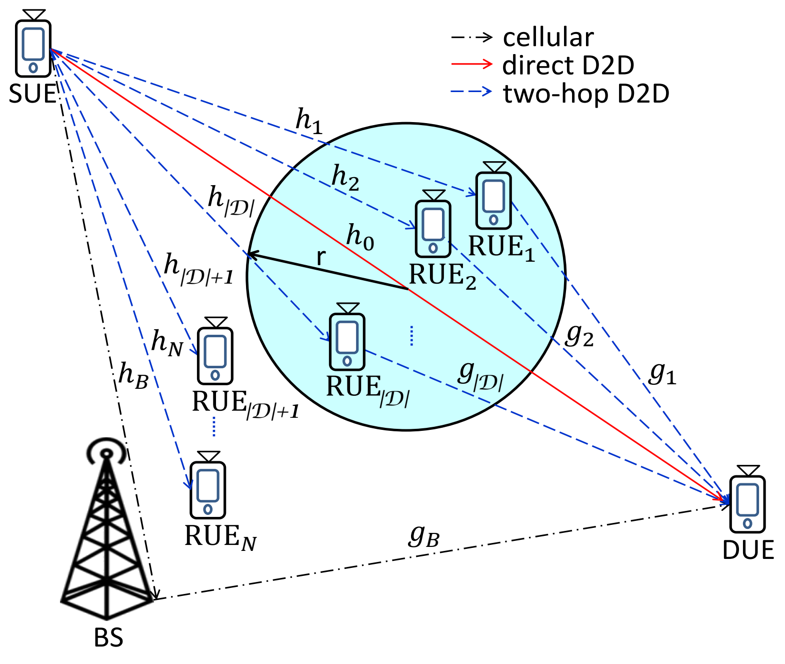


Fig. 5.1 Different communication modes between SUE and DUE.

eligible for forwarding the data. Reciprocal channels and single-antenna nodes are assumed that are subject to the additive white Gaussian noise (AWGN) with power spectral density of N_0. Perfect channel estimation at each node is assumed. The communication between each pair of nodes is performed with fixed rate R (bits/symbol) and bandwidth B (Hz). The scenario with orthogonal channel allocation between cellular and D2D communications is considered [11]. Furthermore, both transmission power and circuit power consumption are taken into account. Each UE has the same circuit power consumption P_C^{UE}, while the BS circuit power consumption is P_C^{BS}. It is assumed that P_C^{UE} and P_C^{BS} are constant and are the same for both transmitter and receiver. All UEs and the BS are constrained by the maximum transmission power P_{MAX}^{UE} and P_{MAX}^{BS}, respectively.

5.2 Two-Hop D2D Communications with the Proposed Forwarding Strategies

In two-hop D2D communications, SUE transmits its data to DUE with the help of DF RUEs that forward the decoded data to DUE.

In this section, two adaptive forwarding strategies for two-hop D2D communications are proposed: an optimal adaptive forwarding strategy (OAFS) and a sub-optimal adaptive forwarding strategy (SAFS). OAFS and SAFS select adaptively between two forwarding modes: BRF and CRB depending on which of them has the higher instantaneous EE. In addition, an approach to select the forwarding mode in a distributed manner is proposed.

5.2.1 Optimal Adaptive Forwarding Strategy (OAFS)

As shown in Fig.5.2, two-hop D2D communications with the proposed OAFS consists of three main activities: training to obtain CSI for both hops at each RUE, forwarding mode selection, and data transmission. The proposed OAFS is summarized in Algorithm 1 and is explained in the following.

Training

At time instants t_0 and t_1, N_T training symbols are transmitted from SUE to RUEs and from DUE to RUEs, respectively. The N available RUEs estimate the corresponding channels. It is assumed that RUE_i (i=1,...,N) are relatively close to each other, resulting in approximately the same distance to SUE (d_{SR}) and to DUE (d_{RD}), respectively.

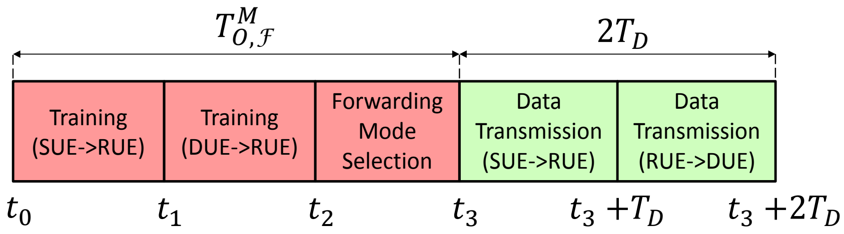


Fig. 5.2 Timing diagram for two-hop D2D communications with the proposed OAFS.

The energy consumed for the training can be calculated as follows,

$$E_T^M = \left(2(N+1)P_C^{UE} + P_T^{S,M} + P_T^{D,M}\right) N_T T_S, \tag{5.1}$$

where,

$$P_T^{S,M} = \frac{1-2^R}{\bar{h}_M \ln(1-\delta_{out})} P_N, \quad \bar{h}_M = 1/\left(PL_D d_{SR}^{\xi_d}\right), \tag{5.2}$$

$$P_T^{D,M} = \frac{1-2^R}{\bar{g}_M \ln(1-\delta_{out})} P_N, \quad \bar{g}_M = 1/\left(PL_D d_{RD}^{\xi_d}\right). \tag{5.3}$$

$T_S = 1/B$ is the symbol duration; $\bar{h}_M$ and $\bar{g}_M$ denote the mean channel power gains of the first hop and the second hop, respectively; $P_N = N_0 B$ denotes the noise power; PL_D is a path loss constant for D2D communications; and ξ_d is the path loss exponent.

All RUE_i (i=1,...,N) with the channel power gains h_i no less than the threshold for successful decoding, $\theta_{th} = (2^R - 1)P_N/P_{MAX}^{UE}$, become part of the main-cluster

$$\mathscr{D} = \{RUE_{1\le i\le N} : h_i \ge \theta_{th}\}.$$

Adaptive Forwarding Strategy

At time $t_2 (> t_1)$, the procedure for forwarding mode selection is initiated, and each UE belonging to the main-cluster $\mathscr{D}$ starts a timer $\tau_j = \lambda/g_j$, where λ is a constant parameter in unit of time [35]. The $RUE_{1:|\mathscr{D}|}$ with the shortest timer $\tau_{1:|\mathscr{D}|}$, i.e., the strongest channel to DUE, becomes part of the forwarding set $\mathscr{F} = \{RUE_{1:|\mathscr{D}|}\}$ and transmits N_T training symbol to SUE with transmission power $P_T^{R,M} = P_T^{S,M}$. All $RUE_j \in \mathscr{D} \setminus \{RUE_{1:|\mathscr{D}|}\}$ put their timers on hold when they overhear the transmission of training symbols from $RUE_{1:|\mathscr{D}|}$. SUE performs channel estimation to obtain the first-hop CSI of $RUE_{1:|\mathscr{D}|}$ and calculates the minimum transmit power to reach $RUE_{1:|\mathscr{D}|}$, $P^{I}_{D,1:|\mathscr{D}|} = \left(2^{R}-1\right) P_N/h_1$.

Due to the broadcast property of wireless channels, the other $RUE_j \in \mathscr{D} \setminus \{RUE_{1:|\mathscr{D}|}\}$ may still correctly decode the data transmitted with power $P^{I}_{D,1:|\mathscr{D}|}$ and can potentially improve the EE through CRB. This is because the RUE with the strongest channel to DUE is selected which does not necessarily have the strongest channel to SUE. As $RUE_j \in \mathscr{D} \setminus \{RUE_{1:|\mathscr{D}|}\}$ do not know $P^{I}_{D,1:|\mathscr{D}|}$ and hence do not know whether they can improve EE or not, SUE broadcasts a triggering symbol with power $P^{I}_{D,1:|\mathscr{D}|}$. All $RUE_j \in \mathscr{D} \setminus \{RUE_{1:|\mathscr{D}|}\}$ that can correctly decode this symbol constitute the RUE sub-cluster

$$\mathscr{S} = \left\{ RUE_j \in \mathscr{D} \setminus \{RUE_{1:|\mathscr{D}|}\} : h_j \geq \frac{(2^R-1)P_N}{P^{I}_{D,1:|\mathscr{D}|}} \right\}$$

and resume their timers.

The best RUE in the sub-cluster $\mathscr{S}$, $RUE_{1:|\mathscr{S}|}$, with the shortest timer $\tau_{1:|\mathscr{S}|}$ becomes part of $\mathscr{F}$, thus CRB is selected as the forwarding strategy, if $RUE_{1:|\mathscr{D}|}$ cannot support target rate R with P^{UE}_{MAX}, i.e., outage occurred or it improves the instantaneous EE (lines 26-29 in Algorithm 1), otherwise BRF is chosen as the forwarding strategy. Subsection 5.2.3 explains in more details how $RUE_{1:|\mathscr{S}|}$ finds out whether one of the conditions mentioned above is satisfied or not. In the case that CRB is selected as forwarding strategy, $RUE_{1:|\mathscr{S}|}$ broadcasts a notification symbol with power

$$P_N^{R,M} = \frac{1-2^R}{\ln(1-\delta_{out})} PL_D (2r)^{\xi_d} P_N, \tag{5.4}$$

which satisfies the target outage probability δ_{out} at the maximum distance $2r$, where r is the radius of main cluster $\mathscr{D}$. As soon as receiving the notification symbol from $RUE_{1:|\mathscr{S}|}$, $RUE_j \in \mathscr{S} \setminus \{RUE_{1:|\mathscr{S}|}\}$ with still unexpired timers will update their timers to $\tau_j = \tau_j + T_S$, in order to avoid possible collisions between RUEs transmissions. The procedure of RUEs joining $\mathscr{F}$, transmitting a notification symbol and remaining RUEs in $\mathscr{S}$ updating their timers (line 28-31) continues with second best, then third best RUEs in $\mathscr{S}$ and so on until all RUEs from $\mathscr{S}$ become part of $\mathscr{F}$ (line 25) or none of the conditions in line 27 is satisfied.

The energy consumption for the forwarding mode selection is given by

$$E^{M}_{S,\mathscr{F}} = \Bigg(\Big((N_T+1)(|\mathscr{D}|+1)+(|\mathscr{F}|-1)(|\mathscr{S}|+1)\Big)P^{UE}_{C} + N_T P^{R,M}_{T} + P^{I}_{D,1:|D|} + (|\mathscr{F}|-1)P^{R,M}_{N}\Bigg)T_S. \tag{5.5}$$

It is composed of two main parts. The first part is the circuit energy consumption for transmission and reception of N_T training symbols transmitted from $RUE_{1:|\mathscr{D}|}$, a triggering symbol broadcast from the source and notification symbols sent from the selected RUEs. The second part represents the related transmission energy consumption for N_T training symbols, a triggering symbol, and $|\mathscr{F}|-1$ notification symbols.

Data Transmission

At time instant $t_3(>t_2)$, the data transmission stage (composed of two equally long time intervals) starts. In the first time interval, SUE transmits data packets with transmission power $P^{I}_{D,1:|\mathscr{D}|}$ that are decoded only by $RUE_i \in \mathscr{F}$. In the second time interval, all $RUE_i \in \mathscr{F}$ forward the decoded data packets with the optimal transmission power given by

$$P^{II}_{D,i} = \begin{cases} (2^R-1)P_N/g_{1:|\mathscr{D}|}, \ BRF \\ (2^R-1)P_N\left(\sum\limits_{RUE_j\in\mathscr{F}} g_j/\sqrt{g_i}\right)^{-2}, \ CRB \end{cases}. \tag{5.6}$$

The overall energy consumed for data transmission is given by

$$E^{M}_{D,\mathscr{F}} = \left(2(1+|\mathscr{F}|)P^{UE}_{C} + P^{I}_{D,1:|\mathscr{D}|} + \sum_{RUE_i\in\mathscr{F}} P^{II}_{D,i}\right)T_D, \tag{5.7}$$

where $T_D = N_D T_S$, and N_D is the number of symbols per data packet. $E^{M}_{D,\mathscr{F}}$ consists of two main components. The first component encompasses circuit energy consumption for source transmitting a data packet and $|\mathscr{F}|$ selected RUEs receiving it as well as $|\mathscr{F}|$ selected RUEs forwarding data packet and destination receiving it. The second component represents the energy consumed for data transmission from the source to the destination over $|\mathscr{F}|$ selected RUEs.

From (5.6) it can be seen that for CRB each $RUE_i \in \mathscr{F}$ needs to know the second-hop channel power gains of all the other $RUE_j \in \mathscr{F}\setminus\{RUE_i\}$, in order to calculate the optimal transmission power. $RUE_i \in \mathscr{F}$ can obtain each others second-hop channel power gains in

Algorithm 1: Two-hop D2D communications with OAFS.

$i = 1$, $l = 1$, $\mathscr{D} = \emptyset$, $\mathscr{S} = \emptyset$;
SUE and DUE transmit N_T training symbols with powers $P_T^{S,M}$ and $P_T^{D,M}$, respectively. Each $RUE_{1 \le i \le N}$, estimates the corresponding h_i and g_i;
$\theta_{th} = (2^R - 1)P_N / P_{MAX}^{UE}$;
while $i \le N$ **do**
  if $h_i \ge \theta_{th}$ **then**
    $\mathscr{D} = \mathscr{D} \cup \{RUE_i\}$;
  end
  $i = i + 1$;
end
All $RUE_j \in \mathscr{D}$, start timers $\tau_j = \lambda / g_j$;
$RUE_{1:|\mathscr{D}|}$ transmits N_T symbols to SUE with power $P_T^{R,M} = P_T^{S,M}$;
$\mathscr{D}_{RES} = \mathscr{D} \setminus \{RUE_{1:|\mathscr{D}|}\}$;
Each $RUE_l \in \mathscr{D}_{RES}$ puts its timer on hold if it overhears transmission from $RUE_{1:|\mathscr{D}|}$;
SUE transmits a triggering symbol with minimum power to reach $RUE_{1:|\mathscr{D}|}$, $P^I_{D,1:|\mathscr{D}|}$;
while $l \le |\mathscr{D}|$ **do**
  if $RUE_l \in \mathscr{D}_{RES}$ && $h_l \ge (2^R - 1)P_N / P^I_{D,1:|\mathscr{D}|}$ **then**
    $\mathscr{S} = \mathscr{S} \cup \{RUE_l\}$;
  end
  $l = l + 1$;
end
$\mathscr{F} = \{RUE_{1:|\mathscr{D}|}\}$;
if $|\mathscr{S}| > 0$ **then**
  All $RUE_i \in \mathscr{S}$ resume their timers τ_i;
  $\mathscr{S}_{RES} = \mathscr{S}$;
  while $|\mathscr{S}_{RES}| > 0$ **do**
    $\mathscr{F}^+ = \mathscr{F} \cup \{RUE_{1:|\mathscr{S}_{RES}|}\}$;
    if $EE^M_{\mathscr{F}} == 0 \; || \; EE^M_{\mathscr{F}^+} > EE^M_{\mathscr{F}}$ **then**
      $\mathscr{F} = \mathscr{F}^+$;
      $RUE_{1:|\mathscr{S}_{RES}|}$ transmits a notification symbol with power $P_N^{R,M}$;
      $\mathscr{S}_{RES} = \mathscr{S}_{RES} \setminus \{RUE_{1:|\mathscr{S}_{RES}|}\}$;
      All $RUE_i \in \mathscr{S}_{RES}$ update their timers $\tau_i = \tau_i + T_S$;
    else
      break;
    end
  end
end
SUE transmits data with power $P^I_{D,1:|\mathscr{D}|}$;
if $|\mathscr{F}| == 1$ **then**
  $RUE_{1:|\mathscr{D}|}$ forwards data to DUE with power $P^{II}_{D,1:|\mathscr{D}|}$;
else
  All $RUE_i \in \mathscr{F}$ cooperatively beamform data towards DUE with powers $P^{II}_{D,i}$;
end

a distributed way through overhearing the notification symbols sent upon the expiration of their timers. It is assumed that at time t_k, $RUE_k \in \mathscr{S} \setminus \{RUE_{j:|\mathscr{S}|}\}$ overhears the notification symbol sent from $RUE_{j:|\mathscr{S}|}$, then $RUE_k \in \mathscr{S} \setminus \{RUE_{j:|\mathscr{S}|}\}$ can acquire $g_{j:|\mathscr{S}|}$ using (4.6) as follows

$$g_{j:|\mathscr{S}|} = \frac{\lambda}{t_k - t_2 - (j+1)T_S}, \tag{5.8}$$

where t_2 is the time instant when all $RUE_j \in \mathscr{D}$ start their timers. It is assumed that the propagation delay within the main cluster $\mathscr{D}$ is negligible compared to the RUE selection time.

Instantaneous EE and SE

The instantaneous EE and SE for two-hop D2D communications with OAFS are given by

$$EE_{\mathscr{F}}^{M} = \begin{cases} \frac{RN_D}{E_T^M + E_{S,\mathscr{F}}^M + E_{D,\mathscr{F}}^M}, & \sum\limits_{RUE_i \in \mathscr{F}} g_i \geq \theta_{th} \\ 0, & otherwise \end{cases}, \tag{5.9}$$

$$SE_{\mathscr{F}}^{M} = \begin{cases} \frac{1}{2}\frac{R}{B}\frac{T_D}{T_D + T_{O,\mathscr{F}}^M}, & \sum\limits_{RUE_i \in \mathscr{F}} g_i \geq \theta_{th} \\ 0, & otherwise \end{cases}, \tag{5.10}$$

where

$$T_{O,\mathscr{F}}^{M} = (3N_T + |\mathscr{F}|)\, T_S + \begin{cases} \lambda / g_{1:|\mathscr{D}|}, & |\mathscr{F}| = 1 \\ \lambda / g_{|\mathscr{F}|-1:|\mathscr{S}|}, & |\mathscr{F}| > 1 \end{cases},$$

is the time consumed for the related overhead. Outage $\left(EE_{\mathscr{F}}^{M} = 0, SE_{\mathscr{F}}^{M} = 0\right)$ occurs when the RUEs in the forwarding set $\mathscr{F}$ cannot support target rate R in the second-hop with P_{MAX}^{UE}.

5.2.2 Sub-Optimal Adaptive Forwarding Strategy (SAFS)

To reduce the computational complexity of (5.12), a low-complexity SAFS is proposed, as shown in Algorithm 2. In SAFS, only the best RUE in $\mathscr{S}$, i.e., with the shortest timer $\tau_{1:|\mathscr{S}|}$, evaluates the condition in (5.12). If (5.12) is satisfied, then CRB is selected as forwarding mode, where $RUE_{1:|\mathscr{D}|}$ and $RUE_{1:|\mathscr{S}|}$ cooperatively forward the received data using the optimal transmission powers given in (5.6). Otherwise, BRF is chosen as the forwarding mode, where only $RUE_{1:|\mathscr{D}|}$ forwards the received data to DUE.

In comparison to OAFS, SAFS may achieve up to $|\mathscr{S}|-1$ fold of complexity reduction, but at the cost of reduced cooperative gains.

Algorithm 2: Two-hop D2D communications with SAFS.

$\mathscr{F} = \{RUE_{1:|\mathscr{D}|}\}$;
if $|\mathscr{S}| > 0$ **then**
  All $RUE_i \in \mathscr{S}$ resume their corresponding timers τ_i;
  $\mathscr{F}^+ = \mathscr{F} \cup \{RUE_{1:|\mathscr{S}|}\}$;
  if $EE^M_{\mathscr{F}^+} > EE^M_{\mathscr{F}}$ **then**
    $\mathscr{F} = \mathscr{F}^+$;
    $RUE_{1:|\mathscr{S}|}$ transmits a notification symbol with power $P_N^{R,M}$;
    All $RUE_i \in \mathscr{S} \setminus \{RUE_{1:|\mathscr{S}|}\}$ reset their timers;
  end
end
SUE transmits data with power $P^I_{D,1:|\mathscr{D}|}$;
if $|\mathscr{F}| == 1$ **then**
  $RUE_{1:|\mathscr{D}|}$ forwards data to DUE with power $P^{II}_{D,1:|\mathscr{D}|}$;
else
  $RUE_{1:|\mathscr{D}|}$ and $RUE_{1:|\mathscr{S}|}$ cooperatively beamform data towards DUE with powers $P^{II}_{D,1:|\mathscr{D}|}$ and $P^{II}_{D,1:|\mathscr{S}|}$, respectively;
end

5.2.3 Distributed Forwarding Mode Selection

$RUE_j \in \mathscr{S}$ joins forwarding set $\mathscr{F}$ when either RUEs in $\mathscr{F}$ are in outage or it improves instantaneous EE, i.e.,

$$\left(EE^M_{\mathscr{F}} = 0\right) \vee \left(EE^M_{\mathscr{F}\cup\{RUE_j\}} > EE^M_{\mathscr{F}}\right). \tag{5.11}$$

$RUE_j \in \mathscr{S}$ possesses all necessary information to evaluate locally the first condition from (5.11) using (5.8) and (5.9).

Due to the dependency of second condition in (5.11) on $|\mathscr{D}|$ and $|\mathscr{S}|$, if $EE^M_{\mathscr{F}} > 0$, $RUE_j \in \mathscr{S}$ does not have all the information to decide autonomously whether to join $\mathscr{F}$ or remain silent. A central entity can be used to collect the first-hop CSI for all RUEs and then signal $|\mathscr{D}|$ and $|\mathscr{S}|$ to $RUE_j \in \mathscr{S}$. However, this centralized solution would increase the energy consumption and reduce SE.

Lemma 1

Independent on $|\mathscr{D}|$ and $|\mathscr{S}|$, for $EE^M_{\mathscr{F}} > 0$ and N known at RUEs, $RUE_j \in \mathscr{S}$ improves instantaneous EE and hence can become part of $\mathscr{F}$ if the associated energy saving for data transmission is higher than the additional energy consumption for forwarding mode selection, i.e.,

$$\Delta E^M_D > \Delta E^M_S, \tag{5.12}$$

where

$$\begin{aligned}
\Delta E^M_S &= E^M_{S,\mathscr{F}\cup\{RUE_j\}} - E^M_{S,\mathscr{F}} = \left((N+1)P^{UE}_C + P^{R,M}_N\right) T_S,\\
\Delta E^M_D &= E^M_{D,\mathscr{F}} - E^M_{D,\mathscr{F}\cup\{RUE_j\}},
\end{aligned}$$

is fulfilled.

Proof. $RUE_j \in \mathscr{S}$ joins forwarding set only for the case that

$$\begin{aligned}
\Delta EE^M &= EE^M_{\mathscr{F}\cup\{RUE_j\}} - EE^M_{\mathscr{F}}\\
&= \frac{RN_D}{E^M_T + E^M_{S,\mathscr{F}\cup\{RUE_j\}} + E^M_{D,\mathscr{F}\cup\{RUE_j\}}} - \frac{RN_D}{E^M_T + E^M_{S,\mathscr{F}} + E^M_{D,\mathscr{F}}} > 0.
\end{aligned} \tag{5.13}$$

(5.13) is satisfied for

$$\Delta E^M_D = E^M_{D,\mathscr{F}} - E^M_{D,\mathscr{F}\cup\{RUE_j\}} > E^M_{S,\mathscr{F}\cup\{RUE_j\}} - E^M_{S,\mathscr{F}} = \Delta E^M_S, \tag{5.14}$$

where using (5.5) leads to

$$\Delta E^M_S = \left((|\mathscr{S}|+1)P^{UE}_C + P^{R,M}_N\right) T_S. \tag{5.15}$$

From (5.15), it can be seen that dependency on $|\mathscr{D}|$ is canceled out. Nevertheless, ΔE^M_S still depends on $|\mathscr{S}|$.

Using $|\mathscr{S}|+1 \leq |\mathscr{D}| \leq N$, upper bound of ΔE^M_S is given by

$$\Delta E^M_S \leq \left((N+1)P^{UE}_C + P^{R,M}_N\right) T_S = \Delta E^{M,U}_S \tag{5.16}$$

For $\Delta E_D^M > \left((N+1)P_C^{UE} + P_N^{R,M}\right) T_S$ and (5.16), it follows that $\Delta E_D^M > \Delta E_S^M$ and (5.13) are satisfied, i.e, $EE^M_{\mathscr{F}\cup\{RUE_j\}} > EE^M_{\mathscr{F}}$. □

5.3 Analysis of Average Energy and Spectral Efficiency

In this section, the average EE and SE under the maximum transmit power constraint is analyzed for OAFS, SAFS, direct D2D communications, and conventional cellular communications.

5.3.1 Two-Hop D2D Communications with the Proposed Adaptive Forwarding Strategies

Without loss of generality, it is assumed that sub-cluster set $\mathscr{S}$ is not empty, i.e., $|\mathscr{S}| > 0$.

Average EE and SE for OAFS

The Average EE for OAFS is given by

$$\mathscr{E}\mathscr{E}_{A1} = \mathbb{E}\left\{ \max_{|\mathscr{F}|\in\{1,\ldots,|\mathscr{S}|+1\}} \left(1 - p_{out}^M(|\mathscr{F}|)\right) EE_{\mathscr{F}}^M(|\mathscr{F}|) \right\}, \tag{5.17}$$

where $p_{out}^M(|\mathscr{F}|) = Pr\left\{ \sum_{RUE_i\in\mathscr{F}} g_i < \theta_{th} \right\}$ is the outage probability in the second-hop of two-hop D2D communications with OAFS. It is very difficult to obtain the exact expression for the expectation in (5.17). Nevertheless, (5.17) can be lower bounded using the following proposition.

Proposition 1

For given $|\mathscr{S}| > 0$, a lower bound of the average EE for OAFS is given by

$$\mathscr{E}\mathscr{E}_{A1} \geq \mathscr{E}\mathscr{E}_{A1}^L(|\mathscr{F}|_{A1}) = \frac{\left(1 - p_{out}^M(|\mathscr{F}|_{A1})\right) RN_D}{E_T^M + \overline{E}_{S,\mathscr{F}}^M(|\mathscr{F}|_{A1}) + \overline{E}_{D,\mathscr{F}}^M(|\mathscr{F}|_{A1})}, \tag{5.18}$$

where $|\mathscr{F}|_{A1}$, $\overline{E}_{S,\mathscr{F}}^M(|\mathscr{F}|_{A1})$, and $\overline{E}_{D,\mathscr{F}}^M(|\mathscr{F}|_{A1})$, are the optimal number of selected RUEs, average energy consumption for forwarding mode selection, and average energy consumed for data transmission, respectively, and are given by

$$|\mathscr{F}|_{A1} = \min\left(\left\lceil\sqrt{\frac{(2^R-1)N_D P_N}{\left((2N_D+|\mathscr{S}|+1)P_C^{UE}+P_N^{R,M}\right)\overline{g}}}\right\rceil, |\mathscr{S}|+1\right), \tag{5.19}$$

$$\begin{aligned}
&p_{out}^{M}(|\mathscr{F}|_{A1}) \approx \frac{|\mathscr{D}|!}{(|\mathscr{D}|-|\mathscr{F}|_{A1})!|\mathscr{F}|_{A1}!}\\
&\left(\frac{\gamma(|\mathscr{F}|_{A1},\theta_{th}/\overline{g})}{(|\mathscr{F}|_{A1}-1)!}+\sum_{l=1}^{|\mathscr{D}|-|\mathscr{F}|_{A1}}\frac{(-1)^{|\mathscr{F}|_{A1}+l-1}(|\mathscr{D}|-|\mathscr{F}|_{A1})!}{(|\mathscr{D}|-|\mathscr{F}|_{A1}-l)!l!}\left(\frac{|\mathscr{F}|_{A1}}{l}\right)^{|\mathscr{F}|_{A1}-1}\right.\\
&\left.\left(\frac{|\mathscr{F}|_{A1}}{|\mathscr{F}|_{A1}+l}\left(1-\exp\left(-\left(1+\frac{l}{|\mathscr{F}|_{A1}}\right)\frac{\theta_{th}}{\overline{g}}\right)-\sum_{m=0}^{|\mathscr{F}|_{A1}-2}\left(-\frac{l}{|\mathscr{F}|_{A1}}\right)^m\frac{\gamma(m+1,\theta_{th}/\overline{g})}{m!}\right)\right)\right),
\end{aligned} \tag{5.20}$$

$$\begin{aligned}
&\overline{E}_{S,\mathscr{F}}^{M}(|\mathscr{F}|_{A1}) = \left(\left((N_T+1)(|\mathscr{D}|+1)+(|\mathscr{F}|_{A1}-1)(|\mathscr{S}|+1)\right)P_C^{UE}+N_T P_T^{R,M}\right.\\
&\left.+(|\mathscr{F}|_{A1}-1)P_N^{R,M}-\left(\frac{2^R-1}{\overline{h}}\right)\exp\left(\frac{\theta_{th}}{\overline{h}}\right)Ei\left(-\frac{\theta_{th}}{\overline{h}}\right)P_N\right)T_S,
\end{aligned} \tag{5.21}$$

$$\begin{aligned}
&\overline{E}_{D,\mathscr{F}}^{M}(|\mathscr{F}|_{A1})\\
&=\left(2(|\mathscr{F}|_{A1}+1)P_C^{UE}-\frac{(2^R-1)}{\overline{h}}\exp\left(\frac{\theta_{th}}{\overline{h}}\right)Ei\left(-\frac{\theta_{th}}{\overline{h}}\right)P_N+\frac{\left(2^R-1\right)|\mathscr{D}|!}{(|\mathscr{D}|-|\mathscr{F}|_{A1})!|\mathscr{F}|_{A1}!\overline{g}}\right.\\
&\left(\frac{\Gamma(|\mathscr{F}|_{A1}-1,\theta_{th}/\overline{g})}{(|\mathscr{F}|_{A1}-1)!}-\sum_{l=1}^{|\mathscr{D}|-|\mathscr{F}|_{A1}}\frac{(-1)^{|\mathscr{F}|_{A1}+l-1}(|\mathscr{D}|-|\mathscr{F}|_{A1})!}{(|\mathscr{D}|-|\mathscr{F}|_{A1}-l)!l!}\left(\frac{|\mathscr{F}|_{A1}}{l}\right)^{|\mathscr{F}|_{A1}-1}\right.\\
&\left.\left(Ei\left(-\left(1+\frac{l}{|\mathscr{F}|_{A1}}\right)\frac{\theta_{th}}{\overline{g}}\right)-Ei\left(-\frac{\theta_{th}}{\overline{g}}\right)+\sum_{m=1}^{|\mathscr{F}|_{A1}-2}\left(-\frac{l}{|\mathscr{F}|_{A1}}\right)^m\frac{\Gamma(m,\theta_{th}/\overline{g})}{m!}\right)\right)\\
&\left(1-\frac{|\mathscr{D}|!}{(|\mathscr{D}|-|\mathscr{F}|_{A1})!|\mathscr{F}|_{A1}!}\left(\frac{\gamma(|\mathscr{F}|_{A1},\theta_{th}/\overline{g})}{(|\mathscr{F}|_{A1}-1)!}+\sum_{l=1}^{|\mathscr{D}|-|\mathscr{F}|_{A1}}\frac{(-1)^{|\mathscr{F}|_{A1}+l-1}(|\mathscr{D}|-|\mathscr{F}|_{A1})!}{(|\mathscr{D}|-|\mathscr{F}|_{A1}-l)!l!}\right.\right.\\
&\left(\frac{|\mathscr{F}|_{A1}}{l}\right)^{|\mathscr{F}|_{A1}-1}\left(\frac{|\mathscr{F}|_{A1}}{|\mathscr{F}|_{A1}+l}\left(1-\exp\left(-\left(1+\frac{l}{|\mathscr{F}|_{A1}}\right)\frac{\theta_{th}}{\overline{g}}\right)\right)\right.\\
&\left.\left.\left.\left.-\sum_{m=0}^{|\mathscr{F}|_{A1}-2}\left(-\frac{l}{|\mathscr{F}|_{A1}}\right)^m\frac{\gamma(m+1,\theta_{th}/\overline{g})}{m!}\right)\right)\right)^{-1}P_N\right)T_D,
\end{aligned} \tag{5.22}$$

with $Ei(x)=\int_{-\infty}^{x}\exp(t)/tdt$, $\Gamma(\alpha,x)=\int_{x}^{\infty}t^{\alpha-1}\exp(-t)dt$ and $\gamma(\alpha,x)=\int_{0}^{x}t^{\alpha-1}\exp(-t)dt$ being the exponential integral function, the upper and lower incomplete gamma functions, respectively [110].

Proof. By means of Jensen's inequality $\mathbb{E}\{\varphi(X)\}\geq\varphi\left(\mathbb{E}\{X\}\right)$, where X is a random variable, (5.17) can be lower bounded as follows

$$\begin{aligned}\mathscr{E}\mathscr{E}_{A1}\geq\mathscr{E}\mathscr{E}_{A1}^{L}&=\max_{|\mathscr{F}|\in\{1,\ldots,|\mathscr{S}|+1\}}\mathbb{E}\{\left(1-p_{out}^{M}(|\mathscr{F}|)\right)EE_{\mathscr{F}}^{M}(|\mathscr{F}|)\}\\&=\left(1-p_{out}^{M}(|\mathscr{F}|_{A1})\right)\mathbb{E}\{EE_{\mathscr{F}}^{M}(|\mathscr{F}|_{A1})\},\end{aligned}\tag{5.23}$$

where

$$\begin{aligned}&p_{out}^{M}(|\mathscr{F}|_{A1})\approx Pr\left\{\sum_{k=1}^{|\mathscr{F}|_{A1}}g_{k:|\mathscr{D}|}<\theta_{th}\right\}=\int_{0}^{\theta_{th}}p_{\sum_{i=1}^{|\mathscr{F}|_{A1}}g_{i:|\mathscr{D}|}}(x)dx\\&=\frac{|\mathscr{D}|!}{(|\mathscr{D}|-|\mathscr{F}|_{A1})!|\mathscr{F}|_{A1}!}\left(\frac{1}{\overline{g}^{|\mathscr{F}|_{A1}}(|\mathscr{F}|_{A1}-1)!}\int_{0}^{\theta_{th}}x^{|\mathscr{F}|_{A1}-1}\exp\left(-\frac{x}{\overline{g}}\right)dx\right.\\&+\frac{1}{\overline{g}}\sum_{l=1}^{|\mathscr{D}|-|\mathscr{F}|_{A1}}(-1)^{l+|\mathscr{F}|_{A1}-1}\frac{(|\mathscr{D}|-|\mathscr{F}|_{A1})!}{(|\mathscr{D}|-|\mathscr{F}|_{A1}-l)!l!}\left(\frac{|\mathscr{F}|_{A1}}{l}\right)^{|\mathscr{F}|_{A1}-1}\\&\left.\left(\int_{0}^{\theta_{th}}\exp\left(-\left(1+\frac{l}{|\mathscr{F}|_{A1}}\right)\frac{x}{\overline{g}}\right)dx-\sum_{m=0}^{|\mathscr{F}|_{A1}-2}\frac{1}{m!}\left(-\frac{l}{|\mathscr{F}|_{A1}\overline{g}}\right)^{m}\int_{0}^{\theta_{th}}x^{m}\exp\left(-\frac{x}{\overline{g}}\right)dx\right)\right),\end{aligned}\tag{5.24}$$

$$|\mathscr{F}|_{A1}=\underset{|\mathscr{F}|\in\{1,\ldots,|\mathscr{S}|+1\}}{\arg\max}\ \mathbb{E}\{\left(1-p_{out}^{M}(|\mathscr{F}|)\right)EE_{\mathscr{F}}^{M}(|\mathscr{F}|)\},\tag{5.25}$$

$$\mathbb{E}\{EE_{\mathscr{F}}^{M}(|\mathscr{F}|_{A1})\}\approx\frac{RN_{D}}{E_{T}^{M}+\overline{E}_{S,\mathscr{F}}^{M}(|\mathscr{F}|_{A1})+\overline{E}_{D,\mathscr{F}}^{M}(|\mathscr{F}|_{A1})}.\tag{5.26}$$

The average energy consumption for forwarding mode selection ($\overline{E}_{S,\mathscr{F}}^{M}(.)$) and data transmission ($\overline{E}_{D,\mathscr{F}}^{M}(.)$) are given by

$$\begin{aligned}&\overline{E}_{S,\mathscr{F}}^{M}(|\mathscr{F}|_{A1})=\left(\left((|\mathscr{D}|+1)P_{C}^{UE}+P_{T}^{R,M}\right)N_{T}+(|\mathscr{D}|+1)P_{C}^{UE}+\left(2^{R}-1\right)P_{N}\right.\\&\left.\mathbb{E}\left\{\frac{1}{h_{1}}|h_{1}\geq\theta_{th}\right\}+(|\mathscr{F}|_{A1}-1)\left((|\mathscr{S}|+1)P_{C}^{UE}+P_{N}^{R,M}\right)\right)T_{S}\end{aligned}$$

$$
= \Bigg(\Big((|\mathscr{D}|+1)P_C^{UE} + P_T^{R,M} \Big) N_T + (|\mathscr{D}|+1)P_C^{UE} + \left(2^R - 1\right) P_N \left(\int_{\theta_{th}}^{\infty} \frac{1}{x} p_{h_1}(x) dx \right) \left(1 - \int_{0}^{\theta_{th}} p_{h_1}(x) dx \right)^{-1} + (|\mathscr{F}|_{A1} - 1) \Big((|\mathscr{S}|+1)P_C^{UE} + P_N^{R,M} \Big) \Bigg) T_S
$$

$$
= \Bigg(\Big((|\mathscr{D}|+1)P_C^{UE} + P_T^{R,M} \Big) N_T + (|\mathscr{D}|+1)P_C^{UE} + \left(2^R - 1\right) P_N \left(\int_{\theta_{th}}^{\infty} \frac{1}{\overline{h}x} \exp\left(-\frac{x}{\overline{h}}\right) dx \right) \left(1 - \int_{0}^{\theta_{th}} \frac{1}{\overline{h}x} \exp\left(-\frac{x}{\overline{h}}\right) dx \right)^{-1} + (|\mathscr{F}|_{A1} - 1) \Big((|\mathscr{S}|+1)P_C^{UE} + P_N^{R,M} \Big) \Bigg) T_S, \tag{5.27}
$$

$$
\overline{E}_{D,\mathscr{F}}^{M}(|\mathscr{F}|_{A1}) = \Bigg(2(1+|\mathscr{F}|_{A1})P_C^{UE} + \left(2^R - 1\right) P_N \left(\mathbb{E}\left\{ \frac{1}{h_1} | h_1 \geq \theta_{th} \right\} + \mathbb{E}\left\{ \left(\sum_{i=1}^{|\mathscr{F}|_{A1}} g_{i:|\mathscr{D}|} \right)^{-1} | \sum_{i=1}^{|\mathscr{F}|_{A1}} g_{i:|\mathscr{D}|} | \geq \theta_{th} \right\} \right) \Bigg) T_D
$$

$$
= \Bigg(2(1+|\mathscr{F}|_{A1})P_C^{UE} + \left(2^R - 1\right) P_N \Bigg(\left(\int_{\theta_{th}}^{\infty} \frac{1}{x} p_{h_1}(x) dx \right) \left(1 - \int_{0}^{\theta_{th}} p_{h_1}(x) dx \right)^{-1} + \left(\int_{\theta_{th}}^{\infty} \frac{1}{x} p_{\sum_{i=1}^{|\mathscr{F}|_{A1}} g_{i:|\mathscr{D}|}}(x) dx \right) \left(1 - \int_{0}^{\theta_{th}} p_{\sum_{i=1}^{|\mathscr{F}|_{A1}} g_{i:|\mathscr{D}|}}(x) dx \right)^{-1} \Bigg) \Bigg) T_D \tag{5.28}
$$

Evaluations of integrals in (5.24), (5.27) and (5.28) lead to (5.20), (5.21) and (5.22), respectively.

In the next step $|\mathscr{F}|_{A1}$ is calculated. Assuming very low outage probability, i.e., $p_{out}^{M}(|\mathscr{F}|) \approx 0$ due to cooperative diversity gains [21], conditional expectations can be replaced by unconditional ones (see Section 3.3). The optimization problem in (5.25) is equivalent to

$$
|\mathscr{F}|_{A1} = \underset{|\mathscr{F}| \in \{1,\dots,|\mathscr{S}|+1\}}{\arg\min} \left(\overline{E}_{S,\mathscr{F}}^{M}(|\mathscr{F}|) + \overline{E}_{D,\mathscr{F}}^{M}(|\mathscr{F}|) \right). \tag{5.29}
$$

Using $\mathbb{E}\left\{\left(\sum\limits_{i=1}^{|\mathscr{F}|} g_{i:|\mathscr{D}|}\right)^{-1}\right\} \approx \mathbb{E}\left\{\left(\sum\limits_{i=1}^{|\mathscr{F}|} g_i\right)^{-1}\right\}$, $\overline{E}^{M}_{D,\mathscr{F}}(|\mathscr{F}|)$ can be approximated as follows

$$\begin{aligned}\overline{E}^{M}_{D,\mathscr{F}}(|\mathscr{F}|) &\approx \left(2\left(1+|\mathscr{F}|\right)P_C^{UE}+\left(2^R-1\right)P_N\left(\mathbb{E}\{g_{1:|\mathscr{D}|}^{-1}\}+\mathbb{E}\left\{\left(\sum_{i=1}^{|\mathscr{F}|} g_i\right)^{-1}\right\}\right)\right)T_D\\ &\approx \left(2\left(1+|\mathscr{F}|\right)P_C^{UE}+\left(2^R-1\right)P_N\left(\mathbb{E}\{g_{1:|\mathscr{D}|}^{-1}\}+\left(|\mathscr{F}|\overline{g}\right)^{-1}\right)\right)T_D. \end{aligned} \tag{5.30}$$

In order to evaluate (5.29), the first derivative of the overall energy consumption needs to satisfy

$$\frac{d}{d|\mathscr{F}|}\left(\overline{E}^{M}_{S,\mathscr{F}}(|\mathscr{F}|)+\overline{E}^{M}_{D,\mathscr{F}}(|\mathscr{F}|)\right)=0, \tag{5.31}$$

where $\overline{E}^{M}_{S,\mathscr{F}}(|\mathscr{F}|)$ and $\overline{E}^{M}_{D,\mathscr{F}}(|\mathscr{F}|)$ are given by (5.27) and (5.30), respectively. Performing the derivation of (5.31) over $|\mathscr{F}|$ and $1 \le |\mathscr{F}|_{A1} \le |\mathscr{S}|+1$ lead to (5.19). $\square$

The average SE for OAFS is given by

$$\mathscr{S}\mathscr{E}_{A1} \approx \frac{1}{2}\left(1-p^{M}_{out}(|\mathscr{F}|_{A1})\right)\frac{R}{B}\frac{T_D}{T_D+\overline{T}^{M}_{O,\mathscr{F}}\left(|\mathscr{F}|_{A1}\right)}, \tag{5.32}$$

where following [109] the average time consumed for overhead when $|\mathscr{F}|_{A1}$ RUEs are selected, is given by

$$\begin{aligned}\overline{T}^{M}_{O,\mathscr{F}}\left(|\mathscr{F}|_{A1}\right) &\approx \left(3N_T+|\mathscr{F}|_{A1}\right)T_S-\lambda\frac{|\mathscr{D}|!}{\overline{g}\left(|\mathscr{F}|_{A1}-1\right)!}\\ &\sum_{i=0}^{|\mathscr{D}|-|\mathscr{F}|_{A1}}\frac{(-1)^i}{\left(|\mathscr{D}|-|\mathscr{F}|_{A1}-i\right)!i!}\int_0^\infty \frac{\exp\left(-\left(i+|\mathscr{F}|_{A1}\right)x\right)}{x}dx, \end{aligned} \tag{5.33}$$

Average EE and SE for SAFS

In SAFS, at most two RUEs are selected to forward the data from SUE to DUE.

Using Proposition 1, a lower bound of the average EE for SAFS can be calculated as follows

$$\mathscr{E}\mathscr{E}_{A2} \ge \mathscr{E}\mathscr{E}^{L}_{A1}\left(|\mathscr{F}|_{A2}\right), \tag{5.34}$$

where

$$|\mathscr{F}|_{A2} = \underset{|\mathscr{F}|=1,2}{\operatorname{argmax}} \left(\mathscr{E}\mathscr{E}_{A1}^{L}(|\mathscr{F}|)\right). \tag{5.35}$$

The average SE for SAFS is given by

$$\mathscr{S}\mathscr{E}_{A2} \approx \frac{1}{2}\left(1 - p_{out}^{M}(|\mathscr{F}|_{A2})\right)\frac{R}{B}\frac{T_D}{T_D + \overline{T}_{O,\mathscr{F}}^{M}(|\mathscr{F}|_{A2})}. \tag{5.36}$$

5.3.2 Direct D2D Communications

In direct D2D communications, SUE directly transmits data to DUE. First, SUE transmits N_T training symbols to DUE with the power

$$P_T^{S,D} = \frac{1-2^R}{\overline{h}_0 \ln(1-\delta_{out})} P_N, \quad \overline{h}_0 = 1/\left(PL_D d_{SD}^{\xi_d}\right). \tag{5.37}$$

The energy consumption for training can be calculated as

$$E_T^D = \left(2P_C^{UE} + P_T^{S,D}\right) N_T T_S, \tag{5.38}$$

Then, DUE performs channel estimation and uses N_{FB} symbols to feed back CSI to SUE with power $P_{FB}^{D,D} = \left(2^R - 1\right) P_N / h_0$.

The energy consumption for the CSI feedback is given by

$$E_{FB}^D = \left(2P_C^{UE} + P_{FB}^{D,D}\right) N_{FB} T_S = \left(2P_C^{UE} + \left(\frac{2^R - 1}{h_0}\right) P_N\right) N_{FB} T_S, \tag{5.39}$$

After reception of CSI, SUE is able to adapt its data transmission power to the minimum level required to support target rate R, $P_D^{S,D} = P_{FB}^{D,D}$, leading to the following energy consumption for data transmission:

$$E_D^D = \left(2P_C^{UE} + P_D^{S,D}\right) T_D = \left(2P_C^{UE} + \left(\frac{2^R - 1}{h_0}\right) P_N\right) T_D,$$

The average EE and SE for direct D2D communications are given respectively by

$$\mathscr{E}\mathscr{E}_D \approx (1 - p_{out}^D) \frac{RN_D}{E_T^D + \overline{E}_{FB}^D + \overline{E}_D^D}, \tag{5.40}$$

$$\mathscr{S}\mathscr{E}_D = (1 - p_{out}^D) \frac{R}{B} \frac{T_D}{T_D + T_O^D}, \tag{5.41}$$

where p_{out}^D is the outage probability, i.e., the probability that the direct D2D link cannot support target rate R with maximum transmission power P_{MAX}^{UE}, and is given by

$$p_{out}^D = Pr\{h_0 < \theta_{th}\} = \int_0^{\theta_{th}} \frac{1}{\overline{h}_0} \exp\left(-\frac{x}{\overline{h}_0}\right) dx = 1 - \exp\left(-\frac{\theta_{th}}{\overline{h}_0}\right); \tag{5.42}$$

$\overline{E}_{FB}^D$ and $\overline{E}_D^D$ are the average energy consumptions for CSI feedback and for data transmission, respectively, and can be calculated as follows

$$\begin{aligned}\overline{E}_{FB}^D &= \left(2P_C^{UE} - \left(2^R - 1\right) P_N \mathbb{E}\left\{\frac{1}{h_0} | h_0 \geq \theta_{th}\right\}\right) N_{FB} T_S = \Bigg(2P_C^{UE} - \left(2^R - 1\right) P_N \\ &\left(\int_{\theta_{th}}^{\infty} \frac{1}{\overline{h}_0 x} \exp\left(-\frac{x}{\overline{h}_0}\right) dx\right) \left(1 - \int_0^{\theta_{th}} \frac{1}{\overline{h}_0} \exp\left(-\frac{x}{\overline{h}_0}\right) dx\right)^{-1}\Bigg) N_{FB} T_S \\ &= \left(2P_C^{UE} - \left(\frac{2^R - 1}{\overline{h}_0}\right) \exp\left(\frac{\theta_{th}}{\overline{h}_0}\right) Ei\left(-\frac{\theta_{th}}{\overline{h}_0}\right) P_N\right) N_{FB} T_S,\end{aligned} \tag{5.43}$$

$$\begin{aligned}\overline{E}_D^D &= \left(2P_C^{UE} - \left(2^R - 1\right) P_N \mathbb{E}\left\{\frac{1}{h_0} | h_0 \geq \theta_{th}\right\}\right) N_{FB} T_S = \Bigg(2P_C^{UE} - \left(2^R - 1\right) P_N \\ &\left(\int_{\theta_{th}}^{\infty} \frac{1}{\overline{h}_0 x} \exp\left(-\frac{x}{\overline{h}_0}\right) dx\right) \left(1 - \int_0^{\theta_{th}} \frac{1}{\overline{h}_0} \exp\left(-\frac{x}{\overline{h}_0}\right) dx\right)^{-1}\Bigg) T_D \\ &= \left(2P_C^{UE} - \left(\frac{2^R - 1}{\overline{h}_0}\right) \exp\left(\frac{\theta_{th}}{\overline{h}_0}\right) Ei\left(-\frac{\theta_{th}}{\overline{h}_0}\right) P_N\right) T_D;\end{aligned} \tag{5.44}$$

and $T_O^D = (N_T + N_{FB}) T_S$ is the overhead time consumption for direct D2D communications.

5.3.3 Cellular Communications

In conventional cellular communications, SUE transmits data to DUE via the BS. Prior to data transmission, N_T training symbols are broadcast from the BS to enable SUE and DUE to estimate their channels to the BS.

The training broadcasting energy for reaching both SUE and DUE is given by

$$E_T^C = \left(P_C^{BS} + 2P_C^{UE} + \max\left\{P_T^{S,C}, P_T^{D,C}\right\}\right) N_T T_S, \tag{5.45}$$

where,

$$P_T^{S,C} = \frac{1-2^R}{\overline{h}_B \ln(1-\delta_{out})} P_N, \quad \overline{h}_B = 1/\left(PL_C d_{SB}^{\xi_c}\right), \tag{5.46}$$

$$P_T^{D,C} = \frac{1-2^R}{\overline{g}_B \ln(1-\delta_{out})} P_N, \quad \overline{g}_B = 1/\left(PL_C d_{BD}^{\xi_c}\right), \tag{5.47}$$

$P_T^{S,C}$ and $P_T^{D,C}$ are the required training transmit power levels from BS to SUE and from BS to DUE, respectively, to satisfy target rate R with outage probability δ_{out}; $\overline{h}_B$ and $\overline{g}_B$ are the mean channel power gains from SUE to BS and from BS to DUE, respectively; PL_C is a path loss constant for cellular communications and ξ_c is the corresponding path loss exponent; d_{SB} and d_{BD} denote the distances from SUE to BS and from BS to DUE, respectively.

Once DUE has estimated its channel to the BS, it feeds back the estimated CSI to BS using N_{FB} symbols with the minimum transmission power that supports target rate R, $P_{FB}^{D,C} = \left(2^R - 1\right) P_N / g_B$.

The energy consumption for the CSI feedback is given by

$$E_{FB}^C = \left(P_C^{UE} + P_C^{BS} + P_{FB}^{D,C}\right) N_{FB} T_S = \left(P_C^{UE} + P_C^{BS} + \left(\frac{2^R - 1}{g_B}\right) P_N\right) N_{FB} T_S, \tag{5.48}$$

During data transmission, SUE transmits data to BS with the adaptive power, $P_D^{S,C} = \left(2^R - 1\right) P_N / h_B$. BS forwards the received data to DUE with transmission power $P_D^{BS} = \left(2^R - 1\right) P_N / g_B$.

The overall energy consumption for the data transmission can be calculated as follows

$$E_D^C = \left(2\left(P_C^{BS} + P_C^{UE}\right) + P_D^{S,C} + P_D^{BS}\right) T_D \tag{5.49}$$

$$= \left(2\left(P_C^{BS} + P_C^{UE}\right) + \left(2^R - 1\right)\left(\frac{1}{h_B} + \frac{1}{g_B}\right) P_N\right) T_D, \tag{5.50}$$

The average EE and SE for cellular communications are given respectively by

$$\mathscr{E}\mathscr{E}_C \approx (1 - p_{out}^{C,I})(1 - p_{out}^{C,II}) \frac{RN_D}{E_T^C + \overline{E}_{FB}^C + \overline{E}_D^C}, \tag{5.51}$$

$$\mathscr{S}\mathscr{E}_C = \frac{1}{2}(1 - p_{out}^{C,I})(1 - p_{out}^{C,II}) \frac{R}{B} \frac{T_D}{T_D + T_O^C}, \tag{5.52}$$

where $T_O^C = (N_T + N_{FB})\, T_S$ denotes the overhead time consumption for cellular communications; The factor 1/2 in (5.52) is due to the two-hop half-duplex transmissions. $p_{out}^{C,I}$ and $p_{out}^{C,II}$ are the outage probabilities for the uplink and downlink transmissions, respectively, and can be calculated as follows

$$p_{out}^{C,I} = Pr\{h_B < \theta_{th}\} = \int_0^{\theta_{th}} \frac{1}{\overline{h}_B} \exp\left(-\frac{x}{\overline{h}_B}\right) dx = 1 - \exp\left(-\theta_{th}/\overline{h}_B\right), \tag{5.53}$$

$$p_{out}^{C,II} = Pr\{g_B < \theta_{th}\} = \int_0^{\theta_{th}} \frac{1}{\overline{g}_B} \exp\left(-\frac{x}{\overline{g}_B}\right) dx = 1 - \exp\left(-\theta_{th}/\overline{g}_B\right); \tag{5.54}$$

and the average energy consumptions for CSI feedback ($\overline{E}_{FB}^C$) and for data transmission ($\overline{E}_D^C$) are given by

$$\begin{aligned}\overline{E}_{FB}^C &= \left(P_C^{UE} + P_C^{BS} - \left(2^R - 1\right) P_N \mathbb{E}\left\{\frac{1}{g_B} | g_B \geq \theta_{th}\right\}\right) N_{FB} T_S = \Bigg(P_C^{UE} + P_C^{BS} - \left(2^R - 1\right) P_N \\ &\quad \left(\int_{\theta_{th}}^{\infty} \frac{1}{\overline{g}_B x} \exp\left(-\frac{x}{\overline{g}_B}\right) dx\right)\left(1 - \int_0^{\theta_{th}} \frac{1}{\overline{g}_B} \exp\left(-\frac{x}{\overline{g}_B}\right) dx\right)^{-1}\Bigg) N_{FB} T_S \\ &= \left(P_C^{UE} + P_C^{BS} - \left(\frac{2^R - 1}{\overline{g}_B}\right) \exp\left(\frac{\theta_{th}}{\overline{g}_B}\right) Ei\left(-\frac{\theta_{th}}{\overline{g}_B}\right) P_N\right) N_{FB} T_S,\end{aligned} \tag{5.55}$$

$$\overline{E}_D^C = \left(2\left(P_C^{BS}+P_C^{UE}\right)-\left(2^R-1\right)\left(\mathbb{E}\left\{\frac{1}{h_B}|h_B\geq\theta_{th}\right\}+\mathbb{E}\left\{\frac{1}{g_B}|g_B\geq\theta_{th}\right\}\right)P_N\right)T_D$$
$$=\left(2\left(P_C^{BS}+P_C^{UE}\right)-\left(2^R-1\right)\right.$$
$$\left(\left(\int_{\theta_{th}}^{\infty}\frac{1}{\overline{h}_B x}\exp\left(-\frac{x}{\overline{h}_B}\right)dx\right)\left(1-\int_0^{\theta_{th}}\frac{1}{\overline{h}_B}\exp\left(-\frac{x}{\overline{h}_B}\right)dx\right)^{-1}\right.$$
$$\left.\left.+\left(\int_{\theta_{th}}^{\infty}\frac{1}{\overline{g}_B x}\exp\left(-\frac{x}{\overline{g}_B}\right)dx\right)\left(1-\int_0^{\theta_{th}}\frac{1}{\overline{g}_B}\exp\left(-\frac{x}{\overline{g}_B}\right)dx\right)^{-1}\right)P_N\right)T_D$$
$$=\left(2\left(P_C^{BS}+P_C^{UE}\right)-\left(2^R-1\right)\right.$$
$$\left.\left(\frac{1}{\overline{h}_B}\exp\left(\frac{\theta_{th}}{\overline{h}_B}\right)Ei\left(-\frac{\theta_{th}}{\overline{h}_B}\right)+\frac{1}{\overline{g}_B}\exp\left(\frac{\theta_{th}}{\overline{g}_B}\right)Ei\left(-\frac{\theta_{th}}{\overline{g}_B}\right)\right)P_N\right)T_D. \tag{5.56}$$

5.4 Simulation Results

The performance of the proposed adaptive forwarding strategies for two-hop D2D communications and the accuracy of the theoretical analysis are evaluated through simulation. Main system parameters are listed in Table 5.1. During training, $N_T = 1$ symbol is transmitted with the power to satisfy the target rate R with outage probability $\delta_{out} = 0.1$. A 64-QAM modulation ($R = 6$) and data packet length of $N_D = 200$ symbols are considered. DUE uses $N_{FB} = 2$ symbols to feedback CSI to BS and to SUE. The radius of main-cluster $\mathscr{D}$ is set to $r = 5m$.

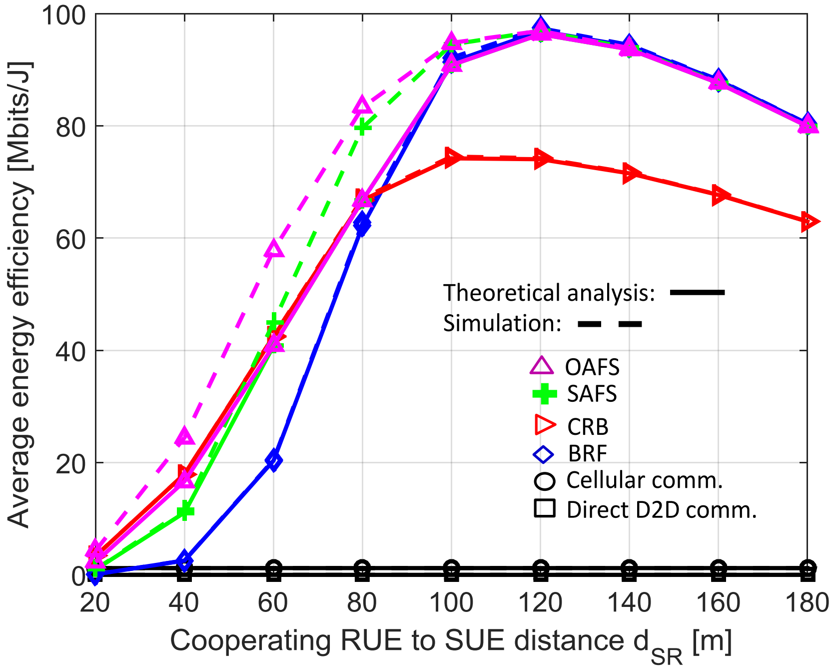
Table 5.1 System parameters

Bandwidth, B	10 MHz
Noise power spectral density, N_0	-174 dBm/Hz
Maximum BS Tx power, P_{MAX}^{BS}	43 dBm
Maximum UE Tx power, P_{MAX}^{UE}	23 dBm
BS circuit power, P_C^{BS}	10 W
UE circuit power, P_C^{UE}	100 mW
Path-loss for cellular communications	128.1 + $37.6\log_{10}[d(km)]$ dB
Path-loss for D2D communications	148 + $40\log_{10}[d(km)]$ dB

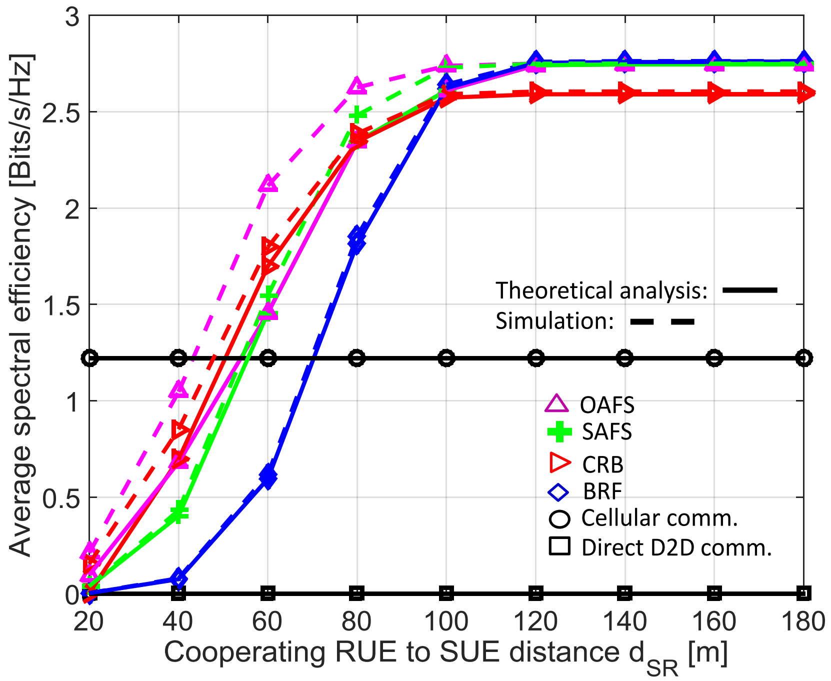
Fig. 5.3(a) plots the average EE versus d_{SR} for the proposed adaptive forwarding strategies, conventional cellular communications, direct D2D communications, BRF [35], and CRB [115] with the optimal number of RUEs, for $d_{SD} = 200m$ and $d_{SB} = d_{BD} = 250m$. Both the simulation and theoretical results are shown. It can be seen that the theoretical lower bounds of average EE for OAFS and SAFS are reasonably tight, while for the other considered communication modes the theoretical results closely match the simulation results. OAFS exhibits the highest average EE when the cooperating RUEs are located closer to SUE. This is because OAFS selects optimally between BRF and CRB. For OAFS, SAFS, BRF and CRB, the average EE initially increases with increasing d_{SR} due to the reduction of transmission power and outage probability in the second-hop; after reaching the maximum, the average EE decreases because the energy consumption in the first hop dominates the overall energy consumption and increases with increasing d_{SR}. For $d_{SR} \geq 80m$, SAFS achieves almost the same average EE as OAFS. Cellular communications is more energy-efficient than direct D2D communications due to lower path-loss resulting in lower transmission power required to satisfy target rate R and lower outage probability.

Fig. 5.3(b) plots the average SE versus d_{SR}. It can be observed that OAFS and SAFS are also more spectral-efficient than BRF for RUEs located closer to SUE. The average SE for OAFS, SAFS, BRF and CRB first increases with increasing d_{SR} due to the reduction of outage probability in the second-hop and then at certain d_{SR} it saturates as no further noticeable reduction of outage probability can be achieved. CRB saturates to the lowest average SE as it needs more overhead that lowers its SE. Cellular communications show the highest average SE for $d_{SR} \leq 40m$ due to the smaller path-loss compared to D2D links resulting in a lower outage probability.

Fig. 5.4(a) plots the average EE versus sub-cluster size $|\mathscr{S}|$ for OAFS, SAFS, BRF and CRB, for $d_{SD} = 150m$. For OAFS and SAFS, the performance under the ideal case, where each RUE knows $|\mathscr{D}|$ and $|\mathscr{S}|$ is also shown. It can be seen that for more realistic cases, where $|\mathscr{D}|$ and $|\mathscr{S}|$ are unknown to RUEs, OAFS and SAFS using distributed forwarding mode selection proposed in Section 5.2.3, perform closely to the corresponding ideal cases. With increasing $|\mathscr{S}|$, the average EE of OAFS, SAFS and CRB increases due to increasing diversity gains. OAFS outperforms all the other forwarding strategies under comparison. SAFS achieves slightly lower average EE than OAFS. Especially for large $|\mathscr{S}|$, the computational complexity of OAFS may be high, making SAFS the preferred forwarding strategy. CRB exhibits the lowest average EE as it performs cooperative beamforming without evaluating whether it improves the instantaneous EE as compared to BRF or not.

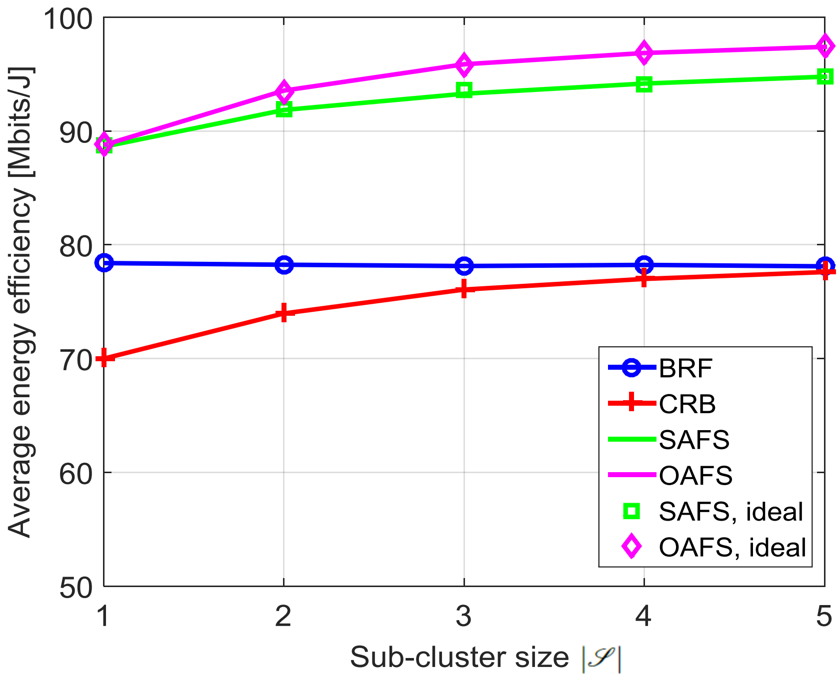


(a) Average energy efficiency

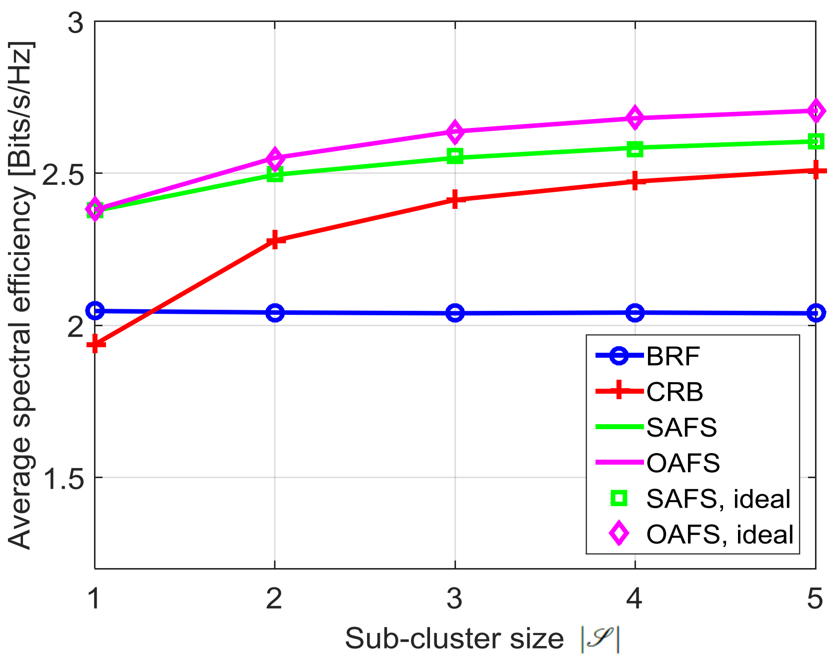


(b) Average spectral efficiency

Fig. 5.3 Average energy and spectral efficiency versus cooperating RUE to SUE distance (d_{SR}) for the proposed forwarding strategies and different communication modes with $d_{SD} = 200m, d_{SB} = d_{BD} = 250m, |\mathscr{D}| = 5$, and $|\mathscr{S}| = 4$.



(a) Average energy efficiency



(b) Average spectral efficiency

Fig. 5.4 Average energy and spectral efficiency comparison between the proposed forwarding strategies, BRF and CRB for different sub-cluster size ($|\mathscr{S}|$) with $d_{SD} = 150m, d_{SR} = 0.2d_{SD}$, and $|\mathscr{D}| = 6$.

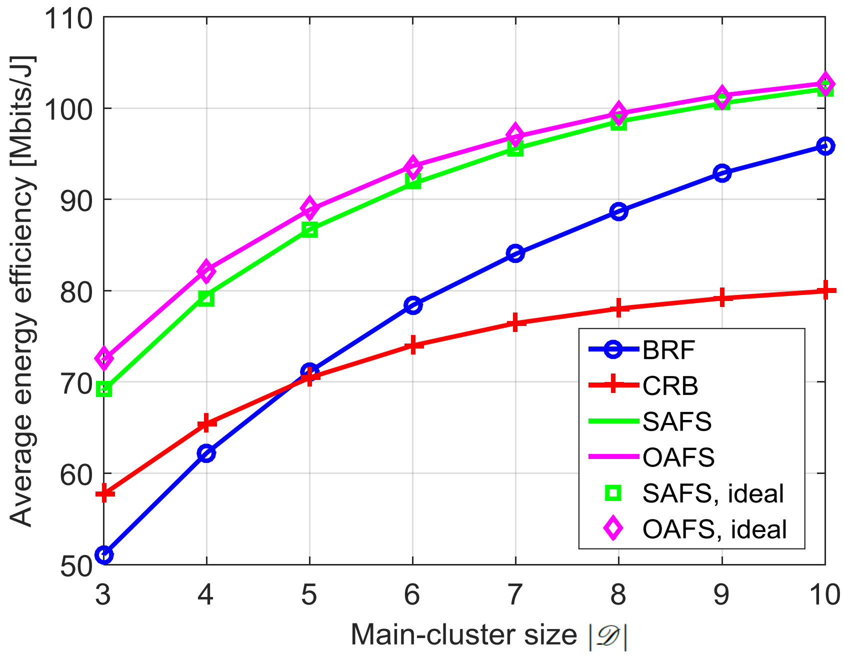
The average SE of OAFS, SAFS, BRF and CRB versus sub-cluster size $|\mathscr{S}|$ for $d_{SD} = 150m$ is depicted in Fig. 5.4(b). With increasing $|\mathscr{S}|$, the average SE of these forwarding strategies increases because of higher diversity gains that lower outage probability. For $|\mathscr{S}| \geq 2$, different from Fig. 5.4(a), CRB is more spectral efficient than BRF. This is because the overhead has a much less impact on SE than on EE and recruiting more than one RUE for forwarding data to DUE reduces outage probability due to cooperative gains.

Fig. 5.5(a) plots the average EE versus main-cluster size $|\mathscr{D}|$ for $|\mathscr{S}| = 2$. For all considered forwarding strategies, increasing $|\mathscr{D}|$ leads to higher average EE due to higher diversity gains. It can be seen that the average EE of the proposed forwarding strategies and CRB saturate at lower values of $|\mathscr{D}|$ than BRF. The reason for this is that with increasing $|\mathscr{D}|$, the proposed forwarding strategies and CRB need more overhead, which starting from a certain $|\mathscr{D}|$ compensate the diversity gains. OAFS and SAFS are more energy-efficient than CRB and BRF independent of $|\mathscr{D}|$ ($3 \leq |\mathscr{D}| \leq 10$). SAFS performs almost as good as OAFS at much lower computation complexity. CRB shows higher average EE than BRF for $3 \leq |\mathscr{D}| < 5$, due to cooperative gains that reduce transmission power and outage probability. For $|\mathscr{D}| > 5$, BRF outperforms CRB due to weaker dependency of its overhead energy consumption on $|\mathscr{D}|$.

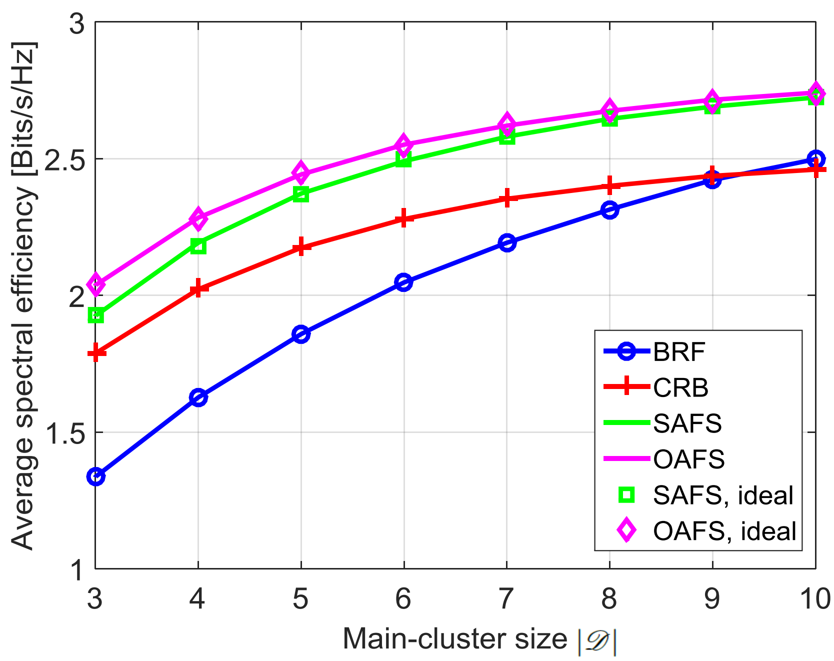
Fig. 5.5(b) shows the average SE versus $|\mathscr{D}|$ for $|\mathscr{S}| = 2$. Due to the same reasons as for 5.5(a), average SE of the considered forwarding strategies increases with increasing $|\mathscr{D}|$ and saturate at different values of $|\mathscr{D}|$. The performance gap between SAFS and OAFS is practically negligible.

Fig. 5.6(a) plots the average EE versus d_{SD} for $d_{SB} = d_{BD} = 300m$. For $d_{SD} < 85m$, direct D2D communications exhibit the highest average EE because of the lowest circuit energy consumption that dominates the overall energy consumption for short SUE to DUE distances. For higher d_{SD}, the proposed forwarding strategies and BRF outperform direct D2D communications due to lower outage probability and reduced transmission power. Furthermore, OAFS and SAFS are more energy-efficient than BRF for $d_{SD} \geq 125m$. For $d_{SD} < 150m$ CRB is less energy-efficient than BRF as its circuit energy consumption is higher because it recruits at least two RUEs for cooperative beamforming. CRB outperforms BRF for $d_{SD} > 150m$, as it has lower outage probability and transmission power due to cooperative gains. Direct cellular communications shows low average EE due to high outage probability and high transmission power.

Fig. 5.6(b) plots average SE versus d_{SD}. It can be observed that direct D2D communications is the most spectral-efficient mode for $d_{SD} < 100m$ as the other modes suffer from spectral-loss of 1/2 due to half-duplex forwarding and need more overhead. For $d_{SD} > 100m$,

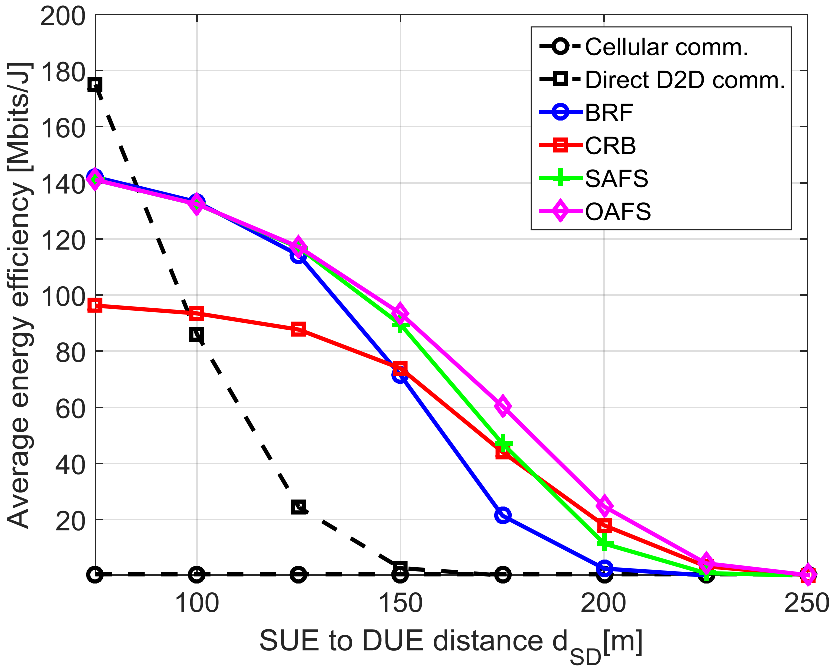


(a) Average energy efficiency

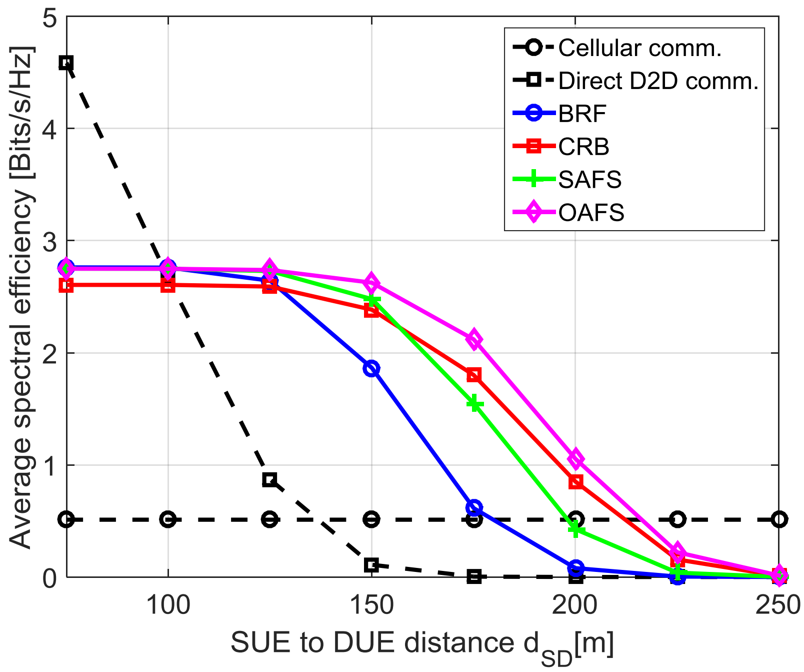


(b) Average spectral efficiency

Fig. 5.5 Average energy and spectral efficiency comparison between the proposed forwarding strategies, BRF and CRB for different main-cluster size ($|\mathscr{D}|$) with $d_{SD} = 150m, d_{SR} = 0.2d_{SD}$, and $|\mathscr{S}| = 2$.

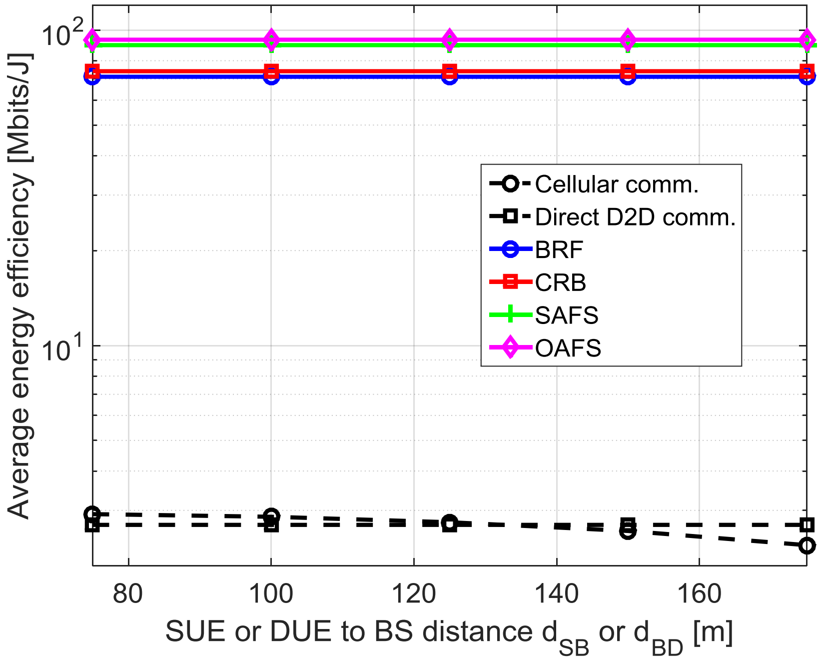


(a) Average energy efficiency

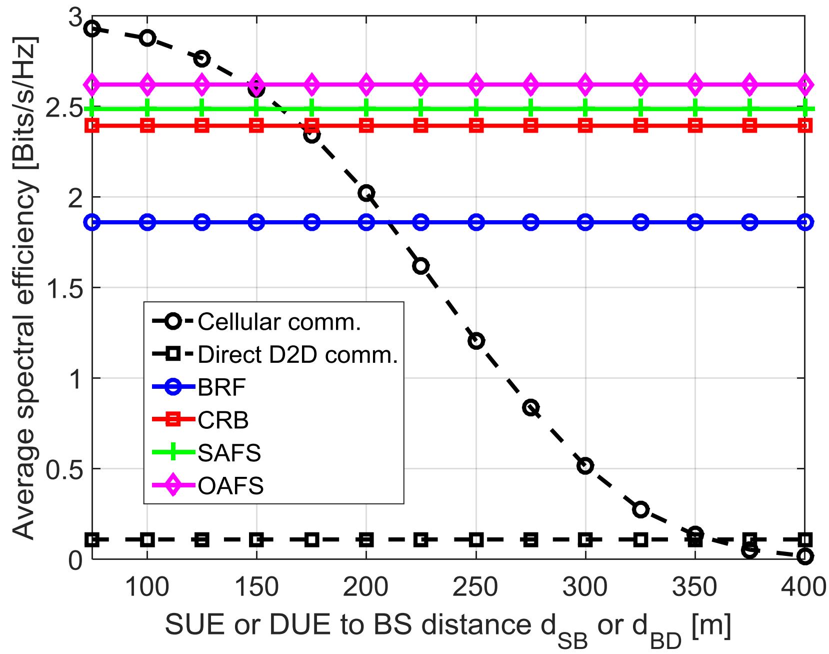


(b) Average spectral efficiency

Fig. 5.6 Average energy and spectral efficiency versus SUE to DUE distance (d_{SD}) for the proposed forwarding strategies and different communication modes with $d_{SB} = d_{BD} = 300m, d_{SR} = 0.2d_{SD}, |\mathscr{D}| = 5$, and $|\mathscr{S}| = 4$.



(a) Average energy efficiency



(b) Average spectral efficiency

Fig. 5.7 Average energy and spectral efficiency versus SUE or DUE to BS distance (d_{SB} or d_{BD}) for the proposed forwarding strategies and different communication modes with $d_{SD} = 150m, d_{SR} = 0.2d_{SD}, |\mathscr{D}| = 5$, and $|\mathscr{S}| = 4$.

the proposed forwarding strategies, BRF and CRB outperform direct D2D communications, which for $d_{SD} > 135m$ is even less spectral-efficient than cellular communications.

Fig. 5.7(a) presents average EE versus d_{SB} or d_{BD}, where $d_{SB} = d_{BD}$ [11] and $d_{SD} = 150m$. It can be seen that the proposed forwarding strategies achieve significantly higher average EE than other communication modes under comparison. Cellular communication shows slightly higher EE than direct D2D communications for $d_{SB} = d_{BD} < 110m$. The average EE of cellular communications decreases with increasing $d_{SB} = d_{BD}$ and falls below the average EE of direct D2D communications for $d_{SB} = d_{BD} > 110m$.

Fig. 5.7(b) plots the average SE versus d_{SB} or d_{BD} for $d_{SD} = 150m$. It can be observed that for $d_{SB} = d_{BD} < 150m$ cellular communications exhibit higher average SE than OAFS as it needs less overhead and has lower outage probability. With increasing d_{SB} or d_{BD} average SE of cellular communications decrease due to increasing outage probability and for $d_{SB} = d_{BD} > 350m$ becomes lower than for direct D2D communications. For d_{SB} or $d_{BD} > 150m$, OAFS is more spectral-efficient than cellular communications and becomes the most spectral-efficient among all communication modes under comparison.

5.5 Summary

In this Chapter, an energy- and spectral-efficient optimal adaptive forwarding strategy (OAFS) for two-hop D2D communications is proposed where RUEs dynamically and in distributed way choose between BRF and CRB with optimal number of RUEs depending on which of them provides the higher instantaneous EE. In order to reduce computational complexity, a low-complexity sub-optimal adaptive forwarding strategy (SAFS) is proposed that selects between BRF and CRB with two RUEs. The average energy-and spectral-efficiency for the proposed forwarding strategies under maximum transmission power constraint is analyzed, considering circuit power consumption and the overhead for obtaining CSI, forwarding mode selection, and cooperative beamforming. The theoretical and simulation results have shown that the proposed OAFS and SAFS are more energy-and spectral-efficient than BRF, CRB, direct D2D communications, and conventional cellular communications. Moreover, the performance of SAFS is close to that of OAFS for short to moderate SUE to DUE distances.

Chapter 6

Conclusions and Future Works

This Chapter concludes the thesis and gives some potential future research directions.

6.1 Conclusions

In this thesis, the energy efficiency (EE) of overhead-aware cooperative communication under realistic conditions considering maximum transmission power constraint and the overhead to acquire channel state information (CSI), select best relays and perform cooperative beamforming, has been studied.

First, for the typical case that not all relays are able to overhear each other's transmissions, an energy-efficient cooperative relaying scheme with low overhead is proposed. In this scheme, a subset of best relays that beamform the received data towards the destination is selected in a proactive way through local timers at relays. For the proposed scheme a closed form approximate expressions for the average EE and optimal relay location are provided. Theoretical and simulation results have indicated that the proposed scheme exhibits significantly higher EE and requires much less overhead than a state-of-the art overhead-aware cooperative relaying scheme. Furthermore, for relays located in the vicinity of source the proposed scheme is more energy-efficient than best relay selection, all relay selection, and direct transmission.

Then, EE of cooperative communications with clustered and location-aware relays is investigated, where relays can overhear the transmission and know the location of each other. An energy-efficient and overhead-aware cooperative beamforming scheme is proposed, where selected relays can calculate optimal beamforming weights without the involvement of the destination through overhearing the transmissions of other selected relays and using location awareness as well as timer based relay selection. In order to avoid collisions between relay transmissions during best relays selection, a distributed protection mechanism is proposed, where selected relays include proper guard intervals prior to their transmissions. An optimal number of relays and their optimal location that maximize EE of the proposed scheme have been identified. The proposed scheme is more energy-efficient than an existing cooperative relaying scheme, best relay selection, all relay selection and direct transmission.

Finally, EE and SE of overhead-aware two-hop D2D communications considering maximum transmit power constraint and constant circuit power consumption is studied. A new energy and spectral efficient optimal adaptive forwarding strategy (OAFS) is proposed that dynamically and in distributed manner switches between best relay forwarding (BRF) and cooperative relay beamforming (CRB) with an optimal number of relay user equipments (RUEs) depending on which of them has higher instantaneous EE. In order to reduce computation complexity, a low-complexity sub-optimal adaptive forwarding strategy (SAFS) is proposed that selects between BRF and CRB with two RUEs based on the instantaneous EE. Average EE and SE of the proposed forwarding strategies taking account of the related overhead for obtaining CSI, forwarding mode selection and cooperative beamforming are analysed theoretically. The analytical and simulation results indicated that the proposed forwarding strategies exhibit higher EE and SE than BRF, CRB with an optimal number of RUEs, direct D2D communications and cellular communications. For short to moderate source UE to destination UE distances, SAFS is nearly as energy and spectral efficient as OAFS.

6.2 Future Works

This thesis could be extended in various directions. Some of the potential research directions for future works are summarized in the following.

6.2.1 Two-Way Cooperative Communications

The proposed energy-efficient cooperative relaying schemes in this thesis utilize half-duplex (HD) decode-and-forward (DF) relays that incur a 1/2 SE loss [7].

Two-way relaying can compensate for SE loss [116]. In the first time slot, UE1 and UE2 transmit their symbols to the DF relay that decodes the received symbols from both UEs. In the next time slot, the DF relay broadcasts the weighted sum of the decoded symbols. Since UE1 and UE2 know their transmitted symbols, self-interference is cancelled at each UE before decoding the transmitted symbols from the other UE.

The EE of two-way relaying has been considered in various works [11][117]-[122]. Nevertheless, the related overhead is usually neglected. Therefore, extending the works in Chapters 3-5 to two-way relaying would be interesting topics for future research.

6.2.2 Radio Frequency (RF) Energy Harvesting Cooperative Relaying

In this thesis, it is assumed that relays have infinite energy buffers and hence relay selection criteria is solely based on channel conditions. In the reality, relays are battery-operated and have limited energy buffers that need to be taken into account during relay selection procedure. Furthermore, recharging or replacing batteries may be very costly.

To this end, energy harvesting has gained a lot of attention recently [123]-[125]. In addition to the typical energy harvesting approaches based on solar, wind, vibration, thermoelectric effects, and so forth, harvesting energy from radio frequency (RF) signals is considered as a new promising solution [126]. Motivation comes from the fact that RF signals transmit simultaneously information and power that can be used at relays to fill their energy buffers. Cooperative communications that harvest energy from RF signal are widely studied [126]-[130]. However, most of the works investigated throughput or outage probability.

EE of cooperative relaying with RF energy harvesting has rarely been considered [131][132]. Thus, introducing relays with RF energy harvesting capabilities in the proposed cooperative relaying schemes would be interesting topics for future research.

6.2.3 Two-Hop D2D Communications Underlying Cellular Networks

In Chapter 5, EE and SE of overhead-aware two-hop D2D communications overlaying cellular networks were investigated. In this case, there exists no interference between D2D UEs and cellular UEs as they use orthogonal channel resources.

The proposed optimal forwarding strategy in Chapter 5 reduces the transmission power and hence generates less interference. A natural extension is to analyse its performance for two-hop D2D communications underlying cellular networks, where interference between D2D UEs and cellular UEs may occur.

References

[1] Z. Hasan, H. Boostanimehr, and V. Bhargava, “Green cellular networks: A survey, some research issues and challenges,” *Communications Surveys Tutorials, IEEE*, vol. 13, no. 4, pp. 524–540, Fourth 2011.

[2] T. Yang, F. Heliot, and C. H. Foh, “A survey of green scheduling schemes for homogeneous and heterogeneous cellular networks,” *IEEE Communications Magazine*, vol. 53, no. 11, pp. 175–181, November 2015.

[3] M. Ismail, W. Zhuang, E. Serpedin, and K. Qaraqe, “A survey on green mobile networking: From the perspectives of network operators and mobile users,” *IEEE Communications Surveys Tutorials*, vol. 17, no. 3, pp. 1535–1556, thirdquarter 2015.

[4] G. Y. Li, Z. Xu, C. Xiong, C. Yang, S. Zhang, Y. Chen, and S. Xu, “Energy-efficient wireless communications: tutorial, survey, and open issues,” *IEEE Wireless Communications*, vol. 18, no. 6, pp. 28–35, December 2011.

[5] D. Feng, C. Jiang, G. Lim, J. Cimini, L.J., G. Feng, and G. Li, “A survey of energy-efficient wireless communications,” *Communications Surveys Tutorials, IEEE*, vol. 15, no. 1, pp. 167–178, First 2013.

[6] A. Sendonaris, E. Erkip, and B. Aazhang, “User cooperation diversity. part i. system description,” *Communications, IEEE Transactions on*, vol. 51, no. 11, pp. 1927–1938, Nov 2003.

[7] J. Laneman, D. Tse, and G. W. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *Information Theory, IEEE Transactions on*, vol. 50, no. 12, pp. 3062–3080, Dec 2004.

[8] D. Feng, L. Lu, Y. Yuan-Wu, G. Y. Li, S. Li, and G. Feng, “Device-to-device communications in cellular networks,” *IEEE Communications Magazine*, vol. 52, no. 4, pp. 49–55, April 2014.

[9] J. Liu, N. Kato, J. Ma, and N. Kadowaki, “Device-to-device communication in lte-advanced networks: A survey,” *IEEE Communications Surveys Tutorials*, vol. 17, no. 4, pp. 1923–1940, Fourthquarter 2015.

[10] X. Ma, R. Yin, G. Yu, and Z. Zhang, “A distributed relay selection method for relay assisted device-to-device communication system,” in *2012 IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC)*, Sept 2012, pp. 1020–1024.

[11] L. Wei, R. Q. Hu, Y. Qian, and G. Wu, “Energy efficiency and spectrum efficiency of multihop device-to-device communications underlaying cellular networks,” *IEEE Transactions on Vehicular Technology*, vol. 65, no. 1, pp. 367–380, Jan 2016.

[12] M. Zorzi and R. R. Rao, “Geographic random forwarding (geraf) for ad hoc and sensor networks: multihop performance,” *IEEE Transactions on Mobile Computing*, vol. 2, no. 4, pp. 337–348, Oct 2003.

[13] Z. Zhou, S. Zhou, J.-H. Cui, and S. Cui, “Energy-efficient cooperative communication based on power control and selective single-relay in wireless sensor networks,” *Wireless Communications, IEEE Transactions on*, vol. 7, no. 8, pp. 3066–3078, August 2008.

[14] M. Nokleby and B. Aazhang, “User cooperation for energy-efficient cellular communications,” in *2010 IEEE International Conference on Communications*, May 2010, pp. 1–5.

[15] S. Cui, A. Goldsmith, and A. Bahai, “Energy-efficiency of mimo and cooperative mimo techniques in sensor networks,” *Selected Areas in Communications, IEEE Journal on*, vol. 22, no. 6, pp. 1089–1098, Aug 2004.

[16] Z. Zhou, S. Zhou, S. Cui, and J.-H. Cui, “Energy-efficient cooperative communication in a clustered wireless sensor network,” *Vehicular Technology, IEEE Transactions on*, vol. 57, no. 6, pp. 3618–3628, Nov 2008.

[17] G. Lim and L. Cimini, “Energy efficiency of cooperative beamforming in wireless ad-hoc networks,” in *Communications (ICC), 2012 IEEE International Conference on*, June 2012, pp. 4039–4043.

[18] Y. Xiao and L. J. Cimini, “Impact of overhead on spectral efficiency of cooperative relaying,” *Wireless Communications, IEEE Transactions on*, vol. 12, no. 5, pp. 2228–2239, May 2013.

[19] Z. Yi and I.-M. Kim, “Joint optimization of relay-precoders and decoders with partial channel side information in cooperative networks,” *Selected Areas in Communications, IEEE Journal on*, vol. 25, no. 2, pp. 447–458, February 2007.

[20] R. Madan, N. Mehta, A. Molisch, and J. Zhang, “Energy-efficient cooperative relaying over fading channels with simple relay selection,” *Wireless Communications, IEEE Transactions on*, vol. 7, no. 8, pp. 3013–3025, August 2008.

[21] G. Lim and J. Cimini, L.J., “Energy-efficient cooperative beamforming in clustered wireless networks,” *Wireless Communications, IEEE Transactions on*, vol. 12, no. 3, pp. 1376–1385, March 2013.

[22] E. C. V. D. Meulen, “Three-terminal communication channels,” *Advances in Applied Probability*, vol. 3, no. 1, pp. 120–154, 1971.

[23] T. Cover and A. Gamal, “Capacity theorems for the relay channel,” *Information Theory, IEEE Transactions on*, vol. 25, no. 5, pp. 572–584, Sep 1979.

[24] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity. part ii. implementation aspects and performance analysis," *Communications, IEEE Transactions on*, vol. 51, no. 11, pp. 1939–1948, Nov 2003.

[25] A. Wyner and J. Ziv, "The rate-distortion function for source coding with side information at the decoder," *IEEE Transactions on Information Theory*, vol. 22, no. 1, pp. 1–10, Jan 1976.

[26] J. Haghighat and W. Hamouda, "Decode-compress-and-forward with selective-cooperation for relay networks," *IEEE Communications Letters*, vol. 16, no. 3, pp. 378–381, March 2012.

[27] Y. Song and N. Devroye, "Lattice codes for the gaussian relay channel: Decode-and-forward and compress-and-forward," *IEEE Transactions on Information Theory*, vol. 59, no. 8, pp. 4927–4948, Aug 2013.

[28] R. Blasco-Serrano, R. Thobaben, M. Andersson, V. Rathi, and M. Skoglund, "Polar codes for cooperative relaying," *IEEE Transactions on Communications*, vol. 60, no. 11, pp. 3263–3273, November 2012.

[29] H. Feng, Y. Xiao, and L. J. Cimini, "Net throughput of centralized and decentralized cooperative networks with relay selection," *IEEE Wireless Communications Letters*, vol. 3, no. 5, pp. 477–480, Oct 2014.

[30] A. Stefanov and E. Erkip, "Cooperative coding for wireless networks," *IEEE Transactions on Communications*, vol. 52, no. 9, pp. 1470–1476, Sept 2004.

[31] ——, "Cooperative space-time coding for wireless networks," *IEEE Transactions on Communications*, vol. 53, no. 11, pp. 1804–1809, Nov 2005.

[32] B. Zhao and M. C. Valenti, "Practical relay networks: a generalization of hybrid-arq," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 1, pp. 7–18, Jan 2005.

[33] Y. Jing and H. Jafarkhani, "Single and multiple relay selection schemes and their achievable diversity orders," *Wireless Communications, IEEE Transactions on*, vol. 8, no. 3, pp. 1414–1423, March 2009.

[34] S. Ikki and M. Ahmed, "Performance analysis of adaptive decode-and-forward cooperative diversity networks with best-relay selection," *Communications, IEEE Transactions on*, vol. 58, no. 1, pp. 68–72, January 2010.

[35] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *Selected Areas in Communications, IEEE Journal on*, vol. 24, no. 3, pp. 659–672, March 2006.

[36] V. Shah, N. Mehta, and R. Yim, "Optimal timer based selection schemes," *Communications, IEEE Transactions on*, vol. 58, no. 6, pp. 1814–1823, June 2010.

[37] R. Talak and N. B. Mehta, "Optimal timer-based best node selection for wireless systems with unknown number of nodes," *Communications, IEEE Transactions on*, vol. 61, no. 11, pp. 4475–4485, November 2013.

[38] M. Zorzi and R. Rao, “Geographic random forwarding (geraf) for ad hoc and sensor networks: energy and latency performance,” *Mobile Computing, IEEE Transactions on*, vol. 2, no. 4, pp. 349–365, Oct 2003.

[39] A. Bletsas, H. Shin, and M. Z. Win, “Cooperative communications with outage-optimal opportunistic relaying,” *IEEE Transactions on Wireless Communications*, vol. 6, no. 9, pp. 3450–3460, September 2007.

[40] B. K. Chalise, Y. D. Zhang, and M. G. Amin, “A novel partial relay selection method for amplify-and-forward relay systems,” in *Global Communications Conference (GLOBECOM), 2012 IEEE*, Dec 2012, pp. 4695–4700.

[41] D. B. da Costa and S. Aissa, “End-to-end performance of dual-hop semi-blind relaying systems with partial relay selection,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 8, pp. 4306–4315, August 2009.

[42] I. Krikidis, J. Thompson, S. Mclaughlin, and N. Goertz, “Amplify-and-forward with partial relay selection,” *IEEE Communications Letters*, vol. 12, no. 4, pp. 235–237, April 2008.

[43] K. S. Hwang, Y. C. Ko, and M. S. Alouini, “Performance analysis of incremental opportunistic relaying over identically and non-identically distributed cooperative paths,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 4, pp. 1953–1961, April 2009.

[44] A. Ibrahim, A. Sadek, W. Su, and K. Liu, “Cooperative communications with relay-selection: when to cooperate and whom to cooperate with?” *Wireless Communications, IEEE Transactions on*, vol. 7, no. 7, pp. 2814–2827, July 2008.

[45] K. Tourki, H. C. Yang, and M. S. Alouini, “Accurate outage analysis of incremental decode-and-forward opportunistic relaying,” *IEEE Transactions on Wireless Communications*, vol. 10, no. 4, pp. 1021–1025, April 2011.

[46] D. Chen and J. N. Laneman, “Modulation and demodulation for cooperative diversity in wireless systems,” *IEEE Transactions on Wireless Communications*, vol. 5, no. 7, pp. 1785–1794, July 2006.

[47] S. S. Ikki and M. H. Ahmed, “Performance analysis of generalized selection combining for amplify-and-forward cooperative-diversity networks,” in *2009 IEEE International Conference on Communications*, June 2009, pp. 1–6.

[48] A. Ribeiro, X. Cai, and G. B. Giannakis, “Symbol error probabilities for general cooperative links,” *IEEE Transactions on Wireless Communications*, vol. 4, no. 3, pp. 1264–1273, May 2005.

[49] M. Chen, S. Serbetli, and A. Yener, “Distributed power allocation strategies for parallel relay networks,” *IEEE Transactions on Wireless Communications*, vol. 7, no. 2, pp. 552–561, February 2008.

[50] W. Choi, D. I. Kim, and B. H. Kim, “Adaptive multi-node incremental relaying for hybrid-arq in af relay networks,” *IEEE Transactions on Wireless Communications*, vol. 9, no. 2, pp. 505–511, February 2010.

[51] B. Hong and W. Choi, "Overcoming half-duplex loss in multi-relay networks: Multiple relay coded cooperation for optimal dmt," *IEEE Transactions on Communications*, vol. 63, no. 1, pp. 66–78, Jan 2015.

[52] R. Mudumbai, G. Barriac, and U. Madhow, "On the feasibility of distributed beamforming in wireless networks," *Wireless Communications, IEEE Transactions on*, vol. 6, no. 5, pp. 1754–1763, May 2007.

[53] Y. Zhao, R. Adve, and T. J. Lim, "Beamforming with limited feedback in amplify-and-forward cooperative networks - [transactions letters]," *Wireless Communications, IEEE Transactions on*, vol. 7, no. 12, pp. 5145–5149, December 2008.

[54] Y. Jing and H. Jafarkhani, "Network beamforming using relays with perfect channel information," *Information Theory, IEEE Transactions on*, vol. 55, no. 6, pp. 2499–2517, June 2009.

[55] Y. Zhang and R. Cheng, "Relay subset selection in cooperative systems with beamforming and limited feedback," *Wireless Communications, IEEE Transactions on*, vol. 12, no. 10, pp. 5271–5281, October 2013.

[56] J. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *Information Theory, IEEE Transactions on*, vol. 49, no. 10, pp. 2415–2425, Oct 2003.

[57] S. Jayaweera, "Virtual mimo-based cooperative communication for energy-constrained wireless sensor networks," *Wireless Communications, IEEE Transactions on*, vol. 5, no. 5, pp. 984–989, May 2006.

[58] Y. Jing and B. Hassibi, "Distributed space-time coding in wireless relay networks," *Wireless Communications, IEEE Transactions on*, vol. 5, no. 12, pp. 3524–3536, December 2006.

[59] J. B. Rao and A. O. Fapojuwo, "A survey of energy efficient resource management techniques for multicell cellular networks," *IEEE Communications Surveys Tutorials*, vol. 16, no. 1, pp. 154–180, First 2014.

[60] K. Davaslioglu and E. Ayanoglu, "Quantifying potential energy efficiency gain in green cellular wireless networks," *IEEE Communications Surveys Tutorials*, vol. 16, no. 4, pp. 2065–2091, Fourthquarter 2014.

[61] G. G. de Oliveira Brante, M. T. Kakitani, and R. D. Souza, "Energy efficiency analysis of some cooperative and non-cooperative transmission schemes in wireless sensor networks," *IEEE Transactions on Communications*, vol. 59, no. 10, pp. 2671–2677, October 2011.

[62] S. Park, W. Lee, and D. h. Cho, "Fair clustering for energy efficiency in a cooperative wireless sensor network," in *2012 IEEE 75th Vehicular Technology Conference (VTC Spring)*, May 2012, pp. 1–5.

[63] B. Li, H. Li, W. Wang, Q. Yin, and H. Liu, "Performance analysis and optimization for energy-efficient cooperative transmission in random wireless sensor network," *IEEE Transactions on Wireless Communications*, vol. 12, no. 9, pp. 4647–4657, September 2013.

[64] D. To, T. To, and J. Choi, "Energy efficient distributed beamforming with sensor selection in wireless sensor networks," in *2012 IEEE 75th Vehicular Technology Conference (VTC Spring)*, May 2012, pp. 1–5.

[65] B. Maham, R. Narasimhan, and A. Hjorungnes, "Energy-efficient space-time coded cooperative routing in multihop wireless networks," in *GLOBECOM 2009 - 2009 IEEE Global Telecommunications Conference*, Nov 2009, pp. 1–7.

[66] J. Zhang, L. Fei, Q. Gao, and X. H. Peng, "Energy-efficient multihop cooperative miso transmission with optimal hop distance in wireless ad hoc networks," *IEEE Transactions on Wireless Communications*, vol. 10, no. 10, pp. 3426–3435, October 2011.

[67] H. Li and G. P. Koudouridis, "An enhanced cooperative relay scheme for energy efficiency and capacity improvements in cellular networks," in *2013 IEEE International Conference on Communications (ICC)*, June 2013, pp. 2459–2463.

[68] N. AbuZainab and A. Ephremides, "Energy efficiency of cooperative relaying over a wireless link," *Wireless Communications, IEEE Transactions on*, vol. 11, no. 6, pp. 2076–2083, June 2012.

[69] Y. Li, C. Liao, Y. Wang, and C. Wang, "Energy-efficient optimal relay selection in cooperative cellular networks based on double auction," *IEEE Transactions on Wireless Communications*, vol. 14, no. 8, pp. 4093–4104, Aug 2015.

[70] F. Librino and M. Zorzi, "Performance of advanced decoding schemes for uplink relaying in cellular networks," *IEEE Transactions on Communications*, vol. 63, no. 1, pp. 79–93, Jan 2015.

[71] O. Amin and L. Lampe, "Opportunistic energy efficient cooperative communication," *Wireless Communications Letters, IEEE*, vol. 1, no. 5, pp. 412–415, October 2012.

[72] G. d. S. Peron, G. Brante, and R. D. Souza, "Energy-efficient distributed power allocation with multiple relays and antenna selection," *IEEE Transactions on Communications*, vol. 63, no. 12, pp. 4797–4808, Dec 2015.

[73] V. Shah, N. Mehta, and R. Yim, "The relay selection and transmission trade-off in cooperative communication systems," *Wireless Communications, IEEE Transactions on*, vol. 9, no. 8, pp. 2505–2515, August 2010.

[74] L. Wei, R. Q. Hu, Y. Qian, and G. Wu, "Enable device-to-device communications underlaying cellular networks: challenges and research aspects," *IEEE Communications Magazine*, vol. 52, no. 6, pp. 90–96, June 2014.

[75] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Communications Surveys Tutorials*, vol. 16, no. 4, pp. 1801–1819, Fourthquarter 2014.

[76] P. Mach, Z. Becvar, and T. Vanek, “In-band device-to-device communication in ofdma cellular networks: A survey and challenges,” *IEEE Communications Surveys Tutorials*, vol. 17, no. 4, pp. 1885–1922, Fourthquarter 2015.

[77] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Miklós, and Z. Turányi, “Design aspects of network assisted device-to-device communications,” *IEEE Communications Magazine*, vol. 50, no. 3, pp. 170–177, March 2012.

[78] Y.-D. Lin and Y.-C. Hsu, “Multihop cellular: a new architecture for wireless communications,” in *Proceedings IEEE INFOCOM 2000. Conference on Computer Communications. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies (Cat. No.00CH37064)*, vol. 3, Mar 2000, pp. 1273–1282 vol.3.

[79] L. Lei, Z. Zhong, C. Lin, and X. Shen, “Operator controlled device-to-device communications in lte-advanced networks,” *IEEE Wireless Communications*, vol. 19, no. 3, pp. 96–104, June 2012.

[80] L. Al-Kanj, H. V. Poor, and Z. Dawy, “Optimal cellular offloading via device-to-device communication networks with fairness constraints,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 8, pp. 4628–4643, Aug 2014.

[81] N. K. Pratas and P. Popovski, “Zero-outage cellular downlink with fixed-rate d2d underlay,” *IEEE Transactions on Wireless Communications*, vol. 14, no. 7, pp. 3533–3543, July 2015.

[82] Q. Ye, M. Al-Shalash, C. Caramanis, and J. G. Andrews, “Distributed resource allocation in device-to-device enhanced cellular networks,” *IEEE Transactions on Communications*, vol. 63, no. 2, pp. 441–454, Feb 2015.

[83] Y. Pei and Y. C. Liang, “Resource allocation for device-to-device communications overlaying two-way cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 12, no. 7, pp. 3611–3621, July 2013.

[84] N. Golrezaei, P. Mansourifard, A. F. Molisch, and A. G. Dimakis, “Base-station assisted device-to-device communications for high-throughput wireless video networks,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 7, pp. 3665–3676, July 2014.

[85] H. Zhang, X. Chu, W. Guo, and S. Wang, “Coexistence of wi-fi and heterogeneous small cell networks sharing unlicensed spectrum,” *IEEE Communications Magazine*, vol. 53, no. 3, pp. 158–164, March 2015.

[86] G. Yu, L. Xu, D. Feng, R. Yin, G. Y. Li, and Y. Jiang, “Joint mode selection and resource allocation for device-to-device communications,” *IEEE Transactions on Communications*, vol. 62, no. 11, pp. 3814–3824, Nov 2014.

[87] D. Zhu, J. Wang, A. L. Swindlehurst, and C. Zhao, “Downlink resource reuse for device-to-device communications underlaying cellular networks,” *IEEE Signal Processing Letters*, vol. 21, no. 5, pp. 531–534, May 2014.

[88] X. Lin, J. G. Andrews, A. Ghosh, and R. Ratasuk, “An overview of 3gpp device-to-device proximity services,” *IEEE Communications Magazine*, vol. 52, no. 4, pp. 40–48, April 2014.

[89] C. Xu, L. Song, Z. Han, Q. Zhao, X. Wang, and B. Jiao, “Interference-aware resource allocation for device-to-device communications as an underlay using sequential second price auction,” in *2012 IEEE International Conference on Communications (ICC)*, June 2012, pp. 445–449.

[90] W. Xu, L. Liang, H. Zhang, S. Jin, J. C. F. Li, and M. Lei, “Performance enhanced transmission in device-to-device communications: Beamforming or interference cancellation?” in *2012 IEEE Global Communications Conference (GLOBECOM)*, Dec 2012, pp. 4296–4301.

[91] R. Zhang, X. Cheng, L. Yang, and B. Jiao, “Interference-aware graph based resource sharing for device-to-device communications underlaying cellular networks,” in *2013 IEEE Wireless Communications and Networking Conference (WCNC)*, April 2013, pp. 140–145.

[92] H. Min, J. Lee, S. Park, and D. Hong, “Capacity enhancement using an interference limited area for device-to-device uplink underlaying cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 10, no. 12, pp. 3995–4000, December 2011.

[93] X. Lin, J. G. Andrews, and A. Ghosh, “Spectrum sharing for device-to-device communication in cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 12, pp. 6727–6740, Dec 2014.

[94] H. ElSawy, E. Hossain, and M. S. Alouini, “Analytical modeling of mode selection and power control for underlay d2d communication in cellular networks,” *IEEE Transactions on Communications*, vol. 62, no. 11, pp. 4147–4161, Nov 2014.

[95] L. Lei, X. . Shen, M. Dohler, C. Lin, and Z. Zhong, “Queuing models with applications to mode selection in device-to-device communications underlaying cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 12, pp. 6697–6715, Dec 2014.

[96] K. Doppler, C. H. Yu, C. B. Ribeiro, and P. Janis, “Mode selection for device-to-device communication underlaying an lte-advanced network,” in *2010 IEEE Wireless Communication and Networking Conference*, April 2010, pp. 1–6.

[97] Y. Huang, A. A. Nasir, S. Durrani, and X. Zhou, “Mode selection, resource allocation, and power control for d2d-enabled two-tier cellular network,” *IEEE Transactions on Communications*, vol. 64, no. 8, pp. 3534–3547, Aug 2016.

[98] D. Wu, J. Wang, R. Q. Hu, Y. Cai, and L. Zhou, “Energy-efficient resource sharing for mobile device-to-device multimedia communications,” *IEEE Transactions on Vehicular Technology*, vol. 63, no. 5, pp. 2093–2103, Jun 2014.

[99] Z. Zhou, M. Dong, K. Ota, J. Wu, and T. Sato, “Distributed interference-aware energy-efficient resource allocation for device-to-device communications underlaying cellular networks,” in *2014 IEEE Global Communications Conference*, Dec 2014, pp. 4454–4459.

[100] F. Wang, C. Xu, L. Song, and Z. Han, “Energy-efficient resource allocation for device-to-device underlay communication,” *IEEE Transactions on Wireless Communications*, vol. 14, no. 4, pp. 2082–2092, April 2015.

[101] D. Feng, G. Yu, C. Xiong, Y. Yuan-Wu, G. Y. Li, G. Feng, and S. Li, “Mode switching for energy-efficient device-to-device communications in cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 14, no. 12, pp. 6993–7003, Dec 2015.

[102] Y. Zhao, Y. Li, H. Zhang, N. Ge, and J. Lu, “Fundamental tradeoffs on energy-aware d2d communication underlaying cellular networks: A dynamic graph approach,” *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 864–882, April 2016.

[103] H. Nishiyama, M. Ito, and N. Kato, “Relay-by-smartphone: realizing multihop device-to-device communications,” *IEEE Communications Magazine*, vol. 52, no. 4, pp. 56–65, April 2014.

[104] M. Hasan, E. Hossain, and D. I. Kim, “Resource allocation under channel uncertainties for relay-aided device-to-device communication underlaying lte-a cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 4, pp. 2322–2338, April 2014.

[105] M. Hasan and E. Hossain, “Distributed resource allocation for relay-aided device-to-device communication: A message passing approach,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 11, pp. 6326–6341, Nov 2014.

[106] ——, “Distributed resource allocation for relay-aided device-to-device communication under channel uncertainties: A stable matching approach,” *IEEE Transactions on Communications*, vol. 63, no. 10, pp. 3882–3897, Oct 2015.

[107] T. Kim and M. Dong, “An iterative hungarian method to joint relay selection and resource allocation for d2d communications,” *IEEE Wireless Communications Letters*, vol. 3, no. 6, pp. 625–628, Dec 2014.

[108] A. Goldsmith and P. Varaiya, “Capacity of fading channels with channel side information,” *Information Theory, IEEE Transactions on*, vol. 43, no. 6, pp. 1986–1992, Nov 1997.

[109] H.-C. Y. M.-S. Alouini, *Order Statistics in Wireless Communications*. Cambridge University Press, 2011.

[110] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*. 6th ed. Academic Press, 2000.

[111] M.-S. Alouini and M. K. Simon, “An mgf-based performance analysis of generalized selection combining over rayleigh fading channels,” *Communications, IEEE Transactions on*, vol. 48, no. 3, pp. 401–415, Mar 2000.

[112] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambrigde University Press, 2004.

[113] 3GPP, *LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation*. 3GPP, TS 36.211 v10.0.0,, 2011.

[114] A. E. Khandani, J. Abounadi, E. Modiano, and L. Zheng, "Cooperative routing in static wireless networks," *IEEE Transactions on Communications*, vol. 55, no. 11, pp. 2185–2192, Nov 2007.

[115] B. Klaiqi, X. Chu, and J. Zhang, "Energy efficiency of location-aware clustered cooperative beamforming without destination feedback," in *2015 IEEE International Conference on Communications (ICC)*, June 2015, pp. 2295–2300.

[116] B. Rankov and A. Wittneben, "Spectral efficient protocols for half-duplex fading relay channels," *Selected Areas in Communications, IEEE Journal on*, vol. 25, no. 2, pp. 379–389, February 2007.

[117] M. Zhou, Q. Cui, R. Jantti, and X. Tao, "Energy-efficient relay selection and power allocation for two-way relay channel with analog network coding," *IEEE Communications Letters*, vol. 16, no. 6, pp. 816–819, June 2012.

[118] C. Sun and C. Yang, "Energy-efficient hybrid one- and two-way relay transmission," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 8, pp. 3737–3751, Oct 2013.

[119] S. Kim and Y. H. Lee, "Energy-efficient power allocation for ofdm signaling over a two-way af relay," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 10, pp. 4856–4863, Oct 2015.

[120] Q. Cui, T. Yuan, X. Tao, A. A. Dowhuszko, and R. Jäntti, "Energy efficiency analysis of two-way df relay system with non-ideal power amplifiers," *IEEE Communications Letters*, vol. 18, no. 7, pp. 1254–1257, July 2014.

[121] C. Xiong, L. Lu, and G. Y. Li, "Energy-efficient ofdma-based two-way relay," *IEEE Transactions on Communications*, vol. 63, no. 9, pp. 3157–3169, Sept 2015.

[122] Q. Cui, T. Yuan, and W. Ni, "Energy-efficient two-way relaying under non-ideal power amplifiers," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 2, pp. 1257–1270, Feb 2017.

[123] S. Luo, R. Zhang, and T. J. Lim, "Optimal save-then-transmit protocol for energy harvesting wireless transmitters," *IEEE Transactions on Wireless Communications*, vol. 12, no. 3, pp. 1196–1207, March 2013.

[124] K. Huang and V. K. N. Lau, "Enabling wireless power transfer in cellular networks: Architecture, modeling and deployment," *IEEE Transactions on Wireless Communications*, vol. 13, no. 2, pp. 902–912, February 2014.

[125] J. Xu and R. Zhang, "Throughput optimal policies for energy harvesting wireless transmitters with non-ideal circuit power," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 2, pp. 322–332, February 2014.

[126] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, “Relaying protocols for wireless energy harvesting and information processing,” *IEEE Transactions on Wireless Communications*, vol. 12, no. 7, pp. 3622–3636, July 2013.

[127] Y. Gu and S. Aïssa, “Rf-based energy harvesting in decode-and-forward relaying systems: Ergodic and outage capacities,” *IEEE Transactions on Wireless Communications*, vol. 14, no. 11, pp. 6425–6434, Nov 2015.

[128] H. Chen, Y. Li, J. L. Rebelatto, B. F. Uchôa-Filho, and B. Vucetic, “Harvest-then-cooperate: Wireless-powered cooperative communications,” *IEEE Transactions on Signal Processing*, vol. 63, no. 7, pp. 1700–1711, April 2015.

[129] R. Tao, A. Salem, and K. A. Hamdi, “Adaptive relaying protocol for wireless power transfer and information processing,” *IEEE Communications Letters*, vol. 20, no. 10, pp. 2027–2030, Oct 2016.

[130] S. Atapattu and J. Evans, “Optimal energy harvesting protocols for wireless relay networks,” *IEEE Transactions on Wireless Communications*, vol. 15, no. 8, pp. 5789–5803, Aug 2016.

[131] S. Guo and X. Zhou, “Energy-efficient design in rf energy harvesting relay networks,” in *2015 IEEE Global Communications Conference (GLOBECOM)*, Dec 2015, pp. 1–6.

[132] S. Guo, F. Wang, Y. Yang, and B. Xiao, “Energy-efficient cooperative tfor simultaneous wireless information and power transfer in clustered wireless sensor networks,” *IEEE Transactions on Communications*, vol. 63, no. 11, pp. 4405–4417, Nov 2015.

Appendix A

A.1 Optimal Relay Transmission Power for Cooperative Beamforming

The received signal at destination for K transmitting relays with weights $w_1, \ldots, w_K$ is given by

$$y_d = \left(\sum_{i=1}^{K} f_i w_i \right) s + n_d, \tag{A.1}$$

where f_i, s, and n_d are channel gain between relay i and destination, transmitted signal with $\mathbb{E}\{|s|^2\} = 1$, and noise at destination, respectively. In order to find the optimal relay transmission power, the following constrained optimization problem needs to be solved

$$\begin{aligned} &\min \sum_{i=1}^{K} |w_i|^2 \\ &s.t. \\ &\frac{\left| \sum_{i=1}^{K} f_i w_i \right|^2}{N_0 B} \geq 2^R - 1. \end{aligned} \tag{A.2}$$

Using Cauchy-Schwarz inequality

$$\left| \sum_{i=1}^{K} f_i w_i \right|^2 \leq \sum_{j=1}^{K} |f_j|^2 \sum_{i=1}^{K} |w_i|^2, \tag{A.3}$$

where for $w_i = cf_i^*$, c being complex number, (A.3) holds with equality and for the optimization problem in (A.2) follows

$$\begin{aligned}
&\min \sum_{i=1}^{K} |w_i|^2 \\
&s.t. \\
&\frac{\sum_{j=1}^{K} |f_j|^2 \sum_{i=1}^{K} |w_i|^2}{N_0 B} \geq 2^R - 1.
\end{aligned} \tag{A.4}$$

Applying KKT conditions [112] to (A.4) yields

$$2|w_i| - 2\lambda |w_i| \sum_{j=1}^{K} |f_j|^2 = 0 \tag{A.5}$$

$$\lambda \left(\sum_{j=1}^{K} |f_j|^2 \sum_{i=1}^{K} |w_i|^2 - N_0 B \left(2^R - 1\right) \right) = 0. \tag{A.6}$$

Since $\lambda > 0$, (A.6) is only satisfied for

$$\sum_{j=1}^{K} |f_j|^2 \sum_{i=1}^{K} |w_i|^2 - N_0 B \left(2^R - 1\right) = 0. \tag{A.7}$$

Using $w_i = cf_i^*$ in (A.7) leads to

$$|c| = \frac{\sqrt{N_0 B \left(2^R - 1\right)}}{\sum_{j=1}^{K} |f_j|^2}. \tag{A.8}$$

It follows then for the optimal transmission power for relay i

$$P_{CB}^{i} = |w_i|^2 = N_0 B \left(2^R - 1\right) \frac{|f_i|^2}{\left(\sum_{j=1}^{K} |f_j|^2\right)^2} = N_0 B \left(2^R - 1\right) \left(\frac{1}{|f_i|} \sum_{j=1}^{K} |f_j|^2 \right)^{-2}. \tag{A.9}$$

For $g_{i:M} = |f_i|^2$, (A.9) yields to (3.17).

A.2 Partial Fraction for Simple Roots

For simple roots holds [110]

$$\frac{\phi(s)}{f(s)} = \frac{A_1}{s-a_1} + \frac{A_2}{s-a_2} + \ldots + \frac{A_M}{s-a_M}, \tag{A.10}$$

where

$$A_k = \frac{\phi(a_k)}{f'(a_k)}, \;\; f(s) = \prod_{i=1}^{M}(s-a_i), \;\; f'(a_k) = \prod_{\substack{i=1 \\ i\neq k}}^{M}(a_k-a_i), \;\; \phi(s) = 1, \tag{A.11}$$

$$\frac{1}{f(s)} = \sum_{k=1}^{M} \frac{A_k}{s-a_k} = \sum_{k=1}^{M} \left(\left(\prod_{\substack{i=1 \\ i\neq k}}^{M}(a_k-a_i) \right) (s-a_k) \right)^{-1}. \tag{A.12}$$